THE FACE OF THE MOON

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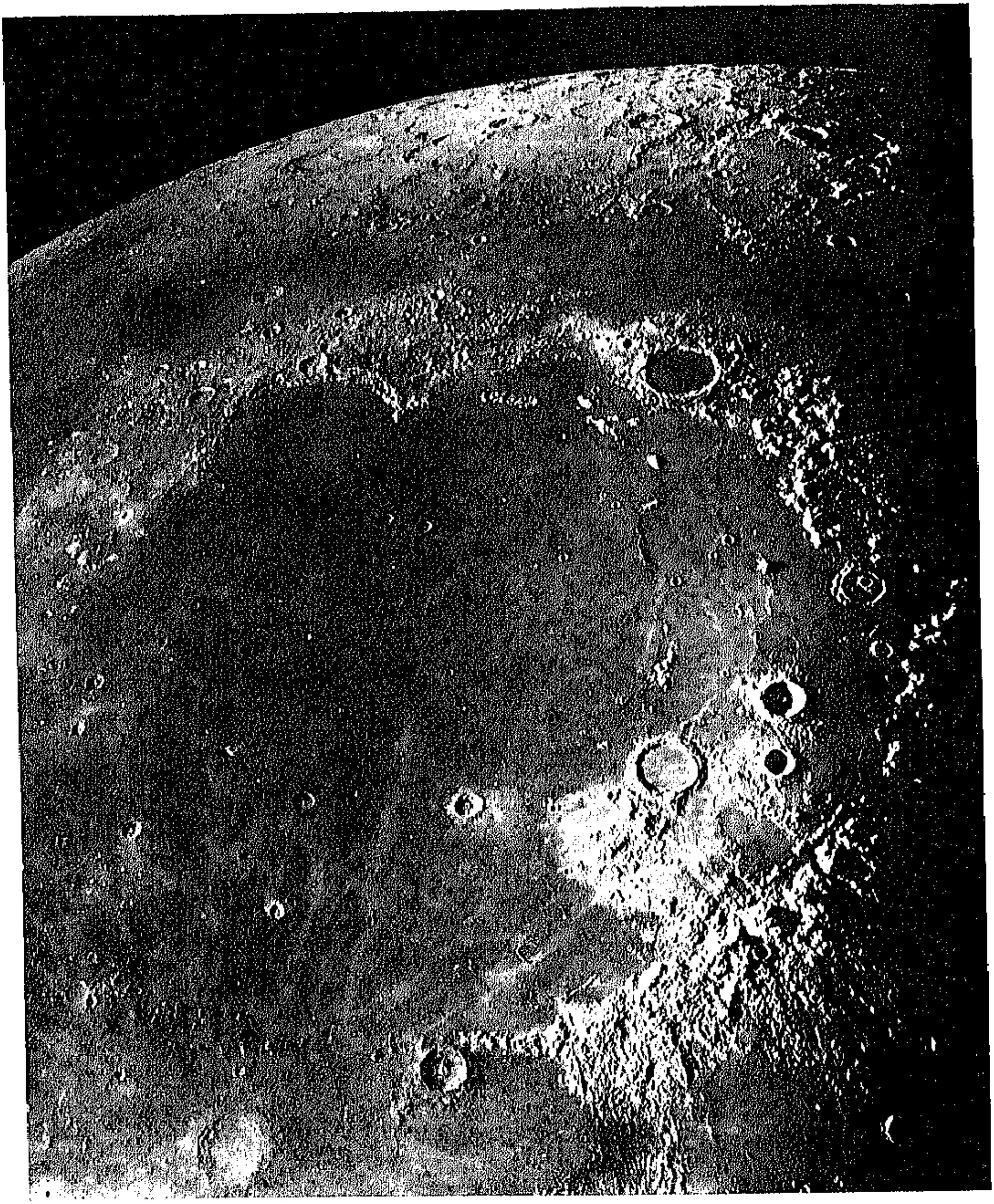

Mare Imbrium, September 15, 1919 (Mt. Wilson)

The FACE of the MOON

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To

MY MOTHER AND FATHER

Who Have Been Sources of
Constant Inspiration

PREFACE

THE moon is undoubtedly one of the driest places in all the universe, but the story of the moon is not at all dry. The slow groping of the ancients for knowledge of the heavens, particularly as it concerns the earth's nearest neighbor, has changed into the quick and lively period of modern astronomical progress. In olden times centuries might pass before a new bit of information was gained about the nature or motions of the moon. Nowadays new facts come tumbling out of the literature like autumn leaves in a brisk wind.

The story of the growth of our understanding of the moon, its nature, and its history is a fascinating one. One of the purposes of this book is to retell this story of the knowledge of the moon gained by scientists of a great many nations from the earliest days to the present. The thread of continual progress may be clearly followed, but here and there are raveled portions where observers and theorists traveled false paths and drew false conclusions.

In spite of, and sometimes because of, these detours the net result was that the nature of the moon's surface and the history of the processes which have affected the moon have been more clearly pointed out.

The major portion of the volume is not historical but is devoted to an extension of our knowledge of the moon based on new observations of the moon and earth and of old observations in a reorganized and reinterpreted form. The main conclusions are thus built on the foundations laid by unnumbered men who have gone before.

In these conclusions is contained an attempt to describe and detect the means by which the primal moon developed to its modern condition and to date as closely as possible the epochs at which the major changes occurred. Numerous correlations have been made with recognized terrestrial data and processes.

Our story, then, starts some thousands of years ago. In the first chapter these centuries are rapidly spanned. The major individual contributions are described and integrated into a picture of the moon which has been accepted generally by scientists.

It is, however, a very incomplete picture. Men have always debated the nature of the processes which have brought the moon to its present dilapidated grandeur. Hence, in chapter 2 we fly out $1\frac{1}{3}$ light-seconds, or 240,000 miles, from the earth and examine in detail the lunar craters, mountain ranges, and lava flows. Even a very brief visit to the moon shows that unusual things have happened there, things not easily explicable in terms of ordinary terrestrial processes.

This point was early recognized, and many astronomers ventured almost as many theories concerning the nature of the moon's surface features. The most important of these suggested mechanisms are discussed in chapter 3, and all but one are discarded as too improbable to warrant further investigation.

The single process which offers promise of being the one which actually operated to build the moon's surface structures is that of meteoritic impact. Meteorites travel very fast and have great kinetic energy. When one strikes the moon, this energy must be released suddenly and thus an explosion occurs. If the meteorite is large enough and moving fast enough, it will carry sufficient energy to produce the equal of any crater now found on the moon.

The fourth and fifth chapters are devoted to a discussion of modern and ancient meteoritic craters known to exist on earth. Old Mother Earth shows a rather pock-marked face, and this is just what we should expect if the moon's craters are meteoritic in nature. The earth and moon would encounter nearly equal numbers of meteorites per unit area. Quite obviously the earth's atmosphere does not offer much protection against such a bombardment of larger masses even though it is a good shield against the more numerous smaller meteorites.

The following three chapters analyze the impact theory in the light of observations on the forms and distributions of lunar craters, terrestrial meteoritic craters, and man-made explosion pits. It is concluded that the craters of the moon have exactly the right shapes and distribution to be explained as simple explosion pits and that the only known source of energy great enough to produce the observed results is that carried by great meteorites.

The existence and the possible effects of a lunar atmosphere are next investigated. It is clear that the moon now possesses no appreciable air and

that it probably never did have an atmosphere capable of seriously affecting the motions of the large meteorites postulated as having formed the main lunar craters.

In the tenth chapter the history of the moon has been traced from its uncertain beginnings, two or three billion years ago, to the present. Its wild variations in distance are correlated with equally drastic changes in the lengths of day and month and also with the height of a tidal bulge in the body of the moon formed by the pull of the earth. Coincident with the recession of the moon was a slumping of the tidal bulge. The solidification of the moon while the tidal bulge was still over a mile high proves to be very significant, for it allows a dating of the origin of the lava flows, or maria, and the majority of the craters. These formations were generated very early in the moon's history.

In the eleventh chapter it is shown that even the maria and the great mountain ranges of the moon can be explained logically by meteoritic impacts and the resultant explosions. In the last and shortest chapter the possibility of meteoritic infalls on other planets is considered.

In its entirety this book presents an internally consistent picture of the past history of the moon in which great numbers of meteorites, large and small, blasted craters in the lunar crust and induced other secondary mechanisms to operate.

But, since the moon has always been the companion of the earth, the history of the former is only a paraphrase of the history of the latter. The prime difference is that on the moon the forces of erosion and water action and mountain building have not operated. On the earth they soon destroyed local surface structures, including meteoritic craters. The study of the moon thus gives us a mirror throughout all time with which to study our own earth.

The vista opened up in this manner is exhilarating in its magnificence, yet it also contains a disturbing factor. There is no assurance that these meteoritic impacts have all been restricted to the past. Indeed we have positive evidence that meteorites or asteroids of the requisite size still abound in space and occasionally come close to the earth.

The explosion which formed the crater Tycho on the moon left us an interesting object to study. A similar occurrence anywhere on the earth would be a horrifying thing, almost inconceivable in its monstrosity.

The story of the face of the moon is a page of history still being written, but its writing covers so vast a period of time that in man's brief existence the action seems to be stopped.

Not only is this story that of a nearly dead body 240,000 miles away, it is also the story of our own earth.

R. B. B.

East Grand Rapids, Michigan
February 1948

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CHAPTER 1

Scientists Look at the Moon

FOR a thousand millenniums primitive man watched the moon. Presumably he used it as a timepiece; certainly it aided him by furnishing light. Sometimes he may have worshiped it as a god or goddess whose favors could be sought or whose angers could be propitiated by appropriate prayers and sacrifices. Questions regarding the moon's true nature and condition probably were never asked until late in man's evolutionary development.

As the human race gradually emerged from the abyss of ignorance, a considerably greater attention was paid to natural phenomena, and crude measurements were made, often, it must be admitted, for religious or political reasons rather than in the scientific spirit.

Perhaps the earliest recorded astronomical occurrence was an eclipse of the sun observed by the Chinese in the year 2158 B.C. The oldest science was not young even then. The Chaldeans, possibly before the time of Abraham, about 2000 B.C., and certainly before 1000 B.C., knew of the saros period[1] and also believed that the earth was spherical. The information about the saros period eventually migrated to Greece, for Thales, according to Herodotus, used it to predict an eclipse in 585 B.C.

Throughout the twenty centuries preceding Christ and on to the invention of the telescope the knowledge of the nature of the moon and of the lunar motions was slowly developed. The earliest scientific work concerned the motions of the moon and their effects on the calendar. In the last three centuries before the Christian Era the early Greek philosophers came to the fore and astronomy became a favorite field. The general resemblance

1. The saros period contains eighteen years $11\frac{1}{3}$ days ($10\frac{1}{3}$ days if there happen to be five leap years on the modern reckoning in the interval). In the saros period the moon makes 223 synodical (6,585.32 days), 239 anomalistic (6,585.54 days), and 242 nodical (6,585.78 days) revolutions; therefore after this period eclipses repeat themselves in order except that their tracks are shifted about 120° westward on the earth.

in the nature of the moon to that of the earth was realized by many of the principal philosophers although probably not by the mass of the people.

Among the writings of Anaxagoras (1)[2] (500–428 B.C.) we find, "The sun places the brightness in the moon." "The moon is eclipsed through the interposition of the earth." "The sun is eclipsed at new moon through the interposition of the moon."

Apparently, however, human nature as well as human curiosity has not changed in over two thousand years. Anaxagoras was accused of impiety for his outrageous beliefs; he taught that the sun was only a red hot stone and that the moon was made of earth, and for holding this doctrine he was banished from Athens.

In spite of the punishment meted out to Anaxagoras other learned men persisted in studying celestial phenomena and objects and reached an amazing level of knowledge.

Democritus (459–370? B.C.) held that the lunar markings, many of which are easily visible to the unaided eye, are caused by great valleys and mountains on the moon's surface. This may be contrasted with the belief held by many medieval scholars who felt that the moon was a great mirror, suspended in space, reflecting the surface features of the earth back to us. Democritus also showed his breadth of vision and imagination by advocating a theory which stated that all matter was composed of individual atoms, hence implying a quantitative rather than a qualitative characteristic to nature.

Aristotle (384–322 B.C.), after proving abstractly that the earth is spherical, says, "The evidence of all the senses further corroborates this. How else would eclipses of the moon show segments as we see them? . . . since it is the interposition of the earth that makes the eclipse, the form of this line (the earth's shadow upon the moon) will be caused by the form of the earth's surface, which is therefore spherical (2)." By continuing in this vein he showed from considerations based on phases and eclipses that the moon must be a sphere always turning the same face to the earth. Similarly he deduced that the moon is nearer than the planet Mars because the latter was occasionally occulted by the moon.

Thus at least twenty-four hundred years ago the ancient philosopher-scientists, working with the unaided eye and unfettered intellect, had come to the conclusion that the moon was a planet, was a globe composed

2. These numbers refer to the Bibliography on pp. 227–32.

of rocks like those of the earth, was marked with great valleys and mountains, and revolved around the earth at a moderate distance. They also recognized that the moon rotated on its axis once in its period of revolution and that this was why men were privileged to see only one side of their lunar companion.

With the advent of the Alexandrian school of Greek philosophers, ancient astronomy developed rapidly. Improved instruments were used, and extended systematic series of observations were made. Aristarchus of Samos (320–250 B.C.) antedated the world-famous Copernicus by eighteen centuries, and yet he, too, was especially distinguished for proposing a heliocentric theory of the solar system, then known to comprise the sun, Mercury, Venus, earth, Mars, Jupiter, Saturn, and the near-by moon. Aristarchus made serious efforts to measure the distances from the earth to the sun and moon. His reasoning was perfect, his instruments less so, and therefore he obtained an entirely inadequate value for the former; but the relative distance to the moon was established, with an error of only 7 per cent, to be fifty-six times the radius of the earth. Strangely enough, he found an apparent diameter of 2° for the moon, four times the true figure.

The work of the mathematician Eratosthenes supplemented that of Aristarchus. By observing the angular difference in zenith position of two places on earth at a known distance apart, he found a radius of 5,000 miles;[3] from other considerations he determined that the sun was 100,000,000 miles away, only 7 per cent too far. His value for the lunar distance was considerably too small, only 98,000 miles.

Hipparchus (190–120 B.C.) was perhaps the greatest of the Greek astronomers. His precise observations carried the theory of the moon's motion to a new perfection. He discovered that the relative motion was not a circle but was an oval. Without the formulation of the law of gravitation he made the reasonable error of assuming that the eccentricity of motion was caused by the earth's being situated eccentrically rather than in the exact center of the moon's circular orbit. Hipparchus also measured the inclination of the lunar path to be 5° to the plane of the earth's orbit around the sun and the period of the revolution of the line of nodes to be eighteen and two-thirds years, much as we know them to be today.

3. Most probable figure. The units used by Eratosthenes are not adequately known, hence our knowledge of the distances he found are correspondingly uncertain.

For the first time the existence of the lunar parallax was realized, and from it Hipparchus determined the moon's distance to be fifty-nine radii of the earth and its diameter to be 31′, values given with almost telescopic accuracy.

Ptolemy (100–170 A.D.), last of the great ancients, went far beyond Hipparchus in the accuracy of his determinations of orbital constants, but his measurements of the lunar distance and diameter were less accurate. The major part of his error resulted from his use of the far too small radius of the earth deduced by Posiedonius.

There the development of our knowledge rested. Like so many other fields of human endeavor, progress in astronomy is never continuous. Periods of wondrous accomplishments are succeeded by stagnant eras, as if the race of scientists were resting and gaining strength for a new assault on the citadel of learning.

This pause lasted for the fourteen centuries until Tycho Brahé (1546–1601 A.D.). This celebrated observer again set the scientific mind into action. Among his other accomplishments he greatly improved the state of knowledge of the motions of the moon, but his prime contribution was the gathering of a great mass of observational data which proved to be vital to the progress of the next century.

The science of astronomy was, however, mainly empirical until three men touched off the fuze of an observational and theoretical bombshell which blasted mankind out of the doldrums of the Dark Ages. Kepler (1571–1630) formulated his famous three laws of planetary motion, and Newton (1642–1727) explained them as natural consequences of his equally famous three laws of motion and of the law of gravitation. The last was itself verified from observations of the moon's motions. Galileo (1564–1642) first applied the telescope to the investigation of the heavens.

The great triumvirate completely revolutionized the scientific world, its concepts, its mode of thinking, and its approach to scientific and technical matters. Without the work of the ancient astronomers, even though parts of it were temporarily lost or disbelieved during the medieval ages, much of the scientific renaissance would have been delayed. Without the advances of Kepler, Newton, and Galileo it would have been impossible. Our modern information about the universe dates primarily from their basic work. In this particular case the knowledge of the motions of the moon and their evaluation, the major physical facts such as the mass of the moon

and its dimensions, are our inheritance from Kepler and Newton. The study of the lunar surface is made possible by the "optik tube" and its descendants.

Knowledge of any phase of astronomy is very like a beautiful cathedral. It is built slowly and carefully over a long period of time. Each worker adds to the foundation stones laid by those who have gone before. Some men make glorious stained glass windows. Others mix mortar. In the case of the story of the moon much has been done; much more remains to be done; the building can never be completed.

The early naked-eye observers of the moon had long realized that there were irregularities on its surface. The southern cusp was occasionally blunted (by the crater Clavius), and the great range of mountains now known as the Apennines caused a very noticeable bulge of the terminator near either quarter-phase. Rarely was the sunrise or sunset line smooth.

In 1610 Galileo's tiny telescope first brought the moon apparently close enough so that it could be easily studied. In spite of relatively poor definition, the strange craters and walled plains were seen and the great arcuate mountain ranges, different in character from any on earth, stood forth boldly. Galileo made a few preliminary sketches and then attempted, rather unsuccessfully, to map the visible surface. He had no micrometer; all sizes and relative positions of objects were obtained from eye estimates. Nevertheless his map was accurate enough to enable him to discover the moon's libration in latitude. He recognized that a diurnal or parallactic libration must exist because of the relative shift in position of the observer and the moon as the earth rotates. A libration is an apparent oscillation of the moon which allows an observer to see a little farther around one limb or another than is usually the case.

Galileo made the first crude efforts to measure lunar heights by estimating the distances beyond the terminator at which the various peaks were still in sunlight. The value derived, $5\frac{1}{4}$ miles, or 28,000 feet, is considerably too great for any objects he could measure in this way.

Langrenus, astronomer at the Spanish court, made numerous drawings of sections of the lunar surface between 1620 and 1640 and apparently was the first to name particular markings. He identified them by the names of prominent men, but the lack of wide publicity and the fact that Hevelius, great astronomer of Danzig, rejected this nomenclature, caused Langrenus' work to be forgotten.

Hevelius in 1647 issued the first satisfactory map of the moon.[4] It designated 250 formations by names of familiar terrestrial objects. His tiny telescope, magnifying only thirty to forty diameters, allowed him to produce this chart which was a standard for over one hundred years.

This great scientist also adopted Galileo's method of determination of mountain heights and found some in the Apennines and Caucasus to be 17,000 feet high, very close to the truth.

Riccioli, the Jesuit of Bologna, in 1651 issued another map of the moon, somewhat inferior to that of Hevelius, but his prime contribution was the overthrow of the Hevelian system of names according to terrestrial analogy and the substitution of names of great men of the seventeenth and earlier centuries. Many of these men had contributed not one whit toward the development of our knowledge of the moon. Riccioli himself and his assistant Grimaldi are immortalized by great craters near the east limb. Nevertheless, in spite of some drawbacks, most of these names are in use today. Riccioli retained the term "mare" (from the Latin word for "sea") from the Hevelian system. The reform attempted later by Gruithuisen, who called them "surfaces," has never taken effect. Six of Hevelius' names are still retained, the Alps, the Apennines, and four promontories.

In 1687 the *Principia*, Newton's masterpiece, appeared, containing brilliant investigations into the ramifications of the celestial applications of the law of gravitation and the laws of motion. In this manuscript was a discussion of the form of the moon on the assumption that the earth's present gravitative pull had distorted the moon into an isopotential surface. He found a theoretical elongation of the radius toward the earth of 186 feet. This form of the moon's figure was held accountable for the identity of the lunar day and month, as a tidal couple would be set up automatically to keep the bulge closely lined up with the centers of the earth and moon. In chapter 10 it will be shown that the moon's bulge is actually much greater than Newton predicted. The physical reason for this discrepancy allows us to date rather accurately the time when the craters and maria were formed.

4. Early maps of the moon: Galileo, 1610; Lagalla, 1612; Scheiner, 1614; Malapert, 1619; Mellan, 1634; Gassendi, 1640; Rheita, 1645; Langrenus, 1645; Fontana, 1646; Hevelius, 1647; Riccioli-Grimaldi, 1651; Kircher, 1660; Montanari, 1662 (based on a primitive micrometer he invented); Cassini, 1680; Tobias Mayer, 1775 (posthumous); Lohrmann, 1824 (partial chart); Beer and Mädler, 1837; Schmidt, 1874; Neison, 1876; Nasmyth and Carpenter, 1874; Elger, 1895.

During these years and subsequently, great mathematicians attacked the problems of the motions of the moon, but for many years little was accomplished to aid in the understanding of the physical nature and history of the moon.

In 1764 Lagrange's memoir (3), which won the French Academy award, showed that the moon's shape must be that of an ellipsoid, as the polar diameter must be compressed by an amount equal to one-third of the excess of the greatest axis, that pointing toward the earth, over the mean. He also proved that the earth's attraction on the moon would have sufficed to force the satellite always to present one face toward its primary even if it had not done so originally.

Laplace (4) recomputed the theoretical tidal bulge of the moon and found it to be 425 feet, much larger than the values Newton and Lagrange had derived, but much smaller than the actual bulge later proved to be.

Laplace was also responsible for developing the nebular hypothesis (1796), first suggested by Kant in 1755, a mechanism to account for the origin of the solar system and, incidentally, the moon. It postulated a gravitational contraction of a huge slowly rotating mass of gas, the primal sun, and the sloughing-off of equatorial rings of gas which later condensed into planets. Repetition of this process formed the satellites, including the moon. This idea was accepted for many years but finally had to be discarded when it was demonstrated that a ring would not coalesce into a single planet, but into many planetoids, and that there was no known way of accounting for the present distribution of angular momentum in the solar system.

In 1791 the *Selenotopographische Fragmente* was published by Schröter of Lilienthal. This was the first major attack on the nature of the lunar surface details and represented seven years' work. The second volume appeared in 1802.

Schröter was the first to measure lunar heights by means of the lengths of their shadows, the same method as is used today. His results, while good, were systematically overestimated; his rough measures of crater diameters were scarcely better than good guesses.

Sixty of the names of structures given by Schröter in expanding Riccioli's list are retained. He also introduced the system of identifying smaller objects by the letters of the Greek and Roman alphabets.

A great deal of Schröter's efforts were spent in trying to establish in-

stances of real changes on the moon. As he did not perfectly realize the great influences of variations of illumination, libration, and earthly atmospheric conditions, he believed that he had found many such points of real change, but in all probability these were entirely optical.

Among Schröter's discoveries was the finding of many rills, the crack-like formations which are so numerous near the edges of the maria, although they are found over much of the surface. These rills, some of which are several miles across, are intimately associated with the birth processes of the maria. The latter are, of course, great lava flows.

Schröter lived to see his observatory, library, and unpublished observations wantonly destroyed by fire by the French under Vandamme in 1813. His life wrecked, he lived but a few years.

In the years 1819 and 1820 Nicollet made a series of thirty-two measures of the position of the crater Manilius at different librations and drew the interesting conclusion that the moon's figure was not a figure of equilibrium, such as it would have assumed had it been liquid. He compared, of course, his derived result with the equilibrium form of the moon at its present distance as computed by Newton, Lagrange, and Laplace.

Poisson pointed out that this conclusion rested on imperfect data, and Nicollet agreed that the problem should be reinvestigated. Much later Franz (5) and Saunder (6) independently did re-examine the problem and corroborated Nicollet's conclusion.

In 1837 Beer and Mädler gave to the world the results of seven years' study. Their book, *Der Mond*, and its chart, "Mappa Selenographica," contained an almost unbelievable amount of information on the details of the lunar surface.

Diameters of 148 craters were measured micrometrically by Mädler, and some approximate measures on less important objects were given. Mädler also measured the height of 830 lunar peaks and crater walls by Schröter's method. In addition, they named nearly 150 new formations, using principally the names of prominent scientists who arose after Riccioli. Several mountain ranges were named, according to Hevelius' system, after terrestrial mountain ranges.

Neison (7) comments:

Upon the conclusion of Beer's and Mädler's fine work the great questions in connection with the physical condition of the moon were generally regarded as finally solved, with perhaps the exception of some of the obscurer phenomena which appeared

likely to baffle all explanation, such as the great ray or streak systems and the rills and clefts; but it was generally regarded as demonstrated that the moon was to all intents an airless, waterless, lifeless, unchangeable desert, with its surface broken by vast extinct volcanoes. With this opinion prevailing, the natural effect of such great works as Beer's and Mädler's speedily ensued, the attention of astronomers was directed to other fields, and Selenography resting on its laurels made no further progress for many years.

It seems strange that the publication of one book, however carefully its material was prepared, could almost completely paralyze for one hundred years the study of the moon by professional astronomers. Beer and Mädler used a refractor of $3\frac{3}{4}$ inches aperture.

Schmidt (8) of Athens in thirty-four years measured and described 32,856 craters and many other objects—a great and useful piece of work which resulted in the publication by the Prussian government in 1878 of a map 75 inches in diameter. For this map Schmidt made over 1,000 drawings. As only 59 per cent of the surface of the moon is visible, there must be, proportionally, about 60,000 craters on the entire surface which would be visible in small telescopes. Many of his measures of crater dimensions, which have aided greatly in setting up important correlations with terrestrial types of craters (chap. 7), are included in Table 4.

Schmidt and others have pointed out several cases of supposed change on the lunar surface, but only at the crater Linné on Mare Serenitatis is there any valid reason to accept the change as real. Many astronomers do not agree that any change has ever been proved.

In 1850 Bond made the first photograph of the moon by the old daguerreotype process. The subsequent evolution of lunar photography is a brilliant facet on the diamond of technical progress.

In 1879 George H. Darwin's monumental contribution, the mathematical treatment of tides, appeared. In this exhaustive work was incorporated a bold suggestion which has had and which will continue to have important effects on our understanding of the moon and its history. It had been known for many years that the moon apparently was accelerating in its motion, and astronomers had come to realize that this speeding up applied to the other bodies of the solar system as well, and hence it could be due only to a decrease in the rate of rotation of the earth. An increase in the length of the day meant a loss of angular momentum, but angular momentum could not be lost, it could only be transferred. What actually was happening was that the tidal interaction of the earth and moon was grad-

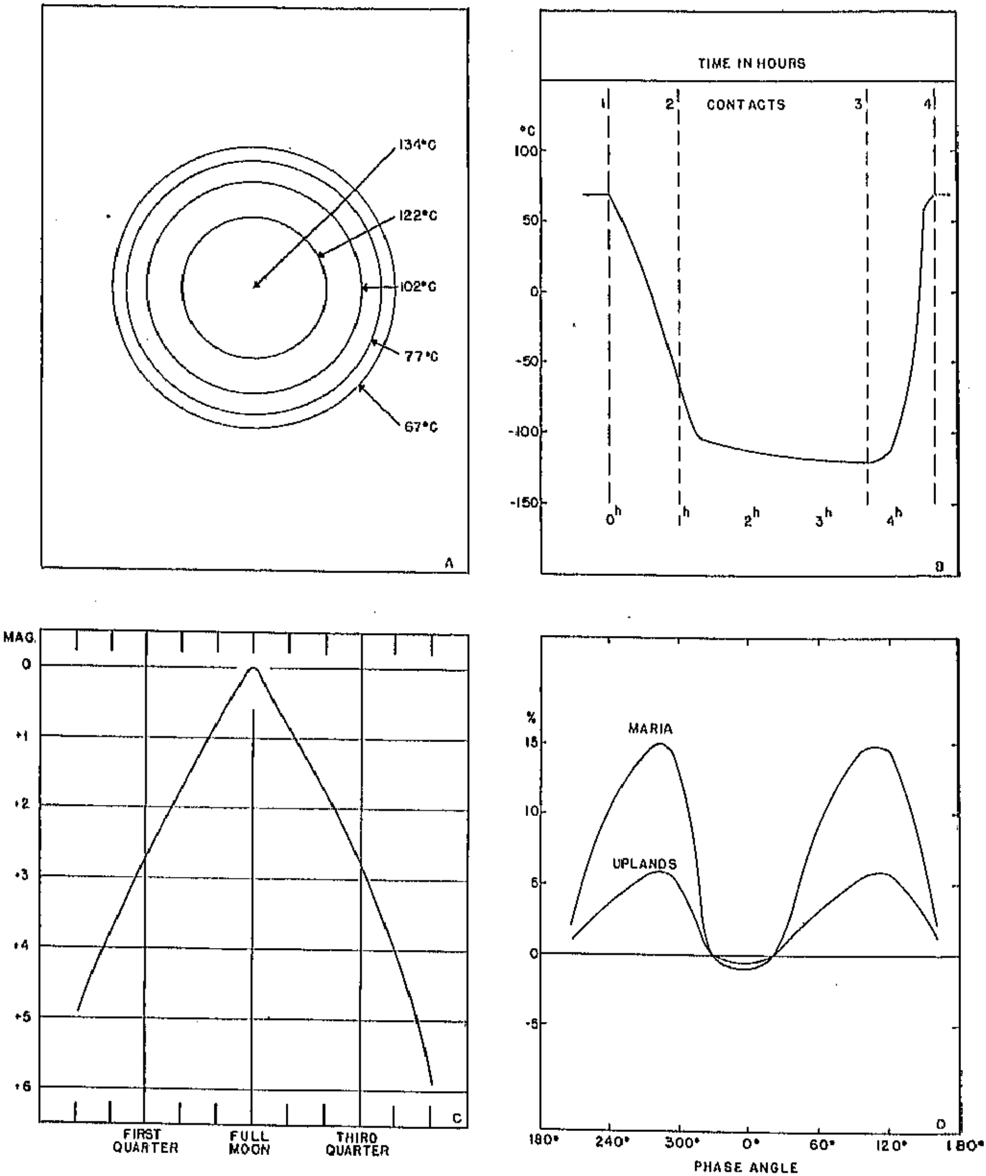


FIG. 1.—The analysis of light from the moon. Upper left: Measured temperatures at full moon (Pettit and Nicholson). Upper right: Temperature variations—eclipse of June 14, 1927 (Pettit). Lower left: The variation of the moon's brightness with phase (Watson [13]). Lower right: Percentage plane polarization vs. phase angle (Lyot).

ually slowing the rotation of the earth and driving the two bodies farther apart, hence maintaining the constancy of the angular momentum in the system.

Darwin extrapolated this process into the past and found that the moon once was close to the earth and that the day and the month were then equal at about four hours. Therefore the solar tide on the earth had a period of two hours, since there are two tides per day. By a remarkable coincidence the slowest natural vibratory period of the earth was also about two hours. Darwin made the reasonable, yet bold, assumption that the resonance of tidal and free vibration in a liquid earth had resulted in the birth of our moon, and this theory was widely held for fifty years. It finally was overthrown when Jeffreys (10) showed that internal friction in the liquid earth would have been too great to allow the resonance bulge to grow to the size where a fission process could occur. It is probable, therefore, that the earth and moon were always separate and distinct bodies.

According to Roche (11), if the earth and moon were always separate bodies, the moon could never have approached the earth, center to center, to a distance less than 2.44 radii of the earth, provided, however, that the two masses were homogeneous and of equal density. Actually both are denser at the center, and the moon is much less in average density than the earth. Therefore the moon can never have been closer than 2.87 radii of the earth, or about 11,000 miles. If it ever were closer than Roche's limit, the moon would have been broken into fragments because of the great tidal distortion.

All the knowledge we have about the moon comes from analysis of the light it sends us. Zöllner (12) has computed, from the measured amount of light received from the moon at different angles, i.e., different portions of the lunar surface at a given phase, that the average slope of the materials composing the moon's crust is 52° from the horizontal in the brighter or so-called "continental" regions.

It is a well-known fact that on earth the angle of repose for most substances is between 30° and 40°. For example, the angle of repose for crushed limestone, iron and copper ores, and similar materials is about 37°, while for Lake Michigan sands it is about 35°. For a lesser gravity, such as would obtain on the moon, the angle of repose would be larger, but not greatly so.

The measured angles of the great slopes on the moon are all relatively small. Consequently, the average value of 52° implies a reflection from a rough, loose surface of cracked stone, not sand, or a surface of steep, rough, and vesicular lava. The smooth and darker color of the maria indicates that the sharp angularity of the uplands is not repeated, at least on as wild a scale.

The importance of these observations is evident, for the nature of the lunar crust was largely determined by the forces which have acted on it since it first solidified.

Over small phase angles near full moon the magnitude (brightness) of the moon changes uniformly with phase angle. The average value (13) over the same phase angles for thirty-four asteroids is 0.030 magnitudes per degree; for the moon it is 0.028 and for Mercury it is 0.032. Mars, Venus, and the earth, which have atmospheres, have similar values around 0.015.

Polarization measures, done at Meudon (14), show that when the fraction of the moon's light which is polarized is plotted against the angle of vision, a characteristic curve is obtained which is found to be similar to that given in the laboratory by a surface covered with a mixture of vol, canic ash. The proportion of the light polarized does not suggest a lava surface in the brighter regions. It varies inversely with the brightness of the portions of the moon which have been examined. The maria give consistently higher values than do the "continental" regions.

It is reasonable to expect that dust and small fragments produced by meteoritic impacts would give results identical to those of volcanic ash. In both cases it is necessary to assume that only the lower portions of the surface are dust filled and that the main apparent features are due to the exposed rock itself, even though it may be extensively jointed and fractured. Probably the form of the surface matter is more important in producing polarization effects than the composition.

The plane polarization of light varies markedly with lunar phase angle. For the maria there is a maximum polarization at phase angles 100°–110° and at 280°–290°. The peak values range between 10 per cent and 16 per cent for different maria. There is zero polarization at 22°–23° and at 327°–328°. At 0° (full moon) there is a slight negative polarization, around 1 per cent. Lyot has found a similar effect for terrestrial objects.

In the mountainous regions there is an identical variation in the per-

centage of plane polarization, in phase with the curves from the maria, but of one-half the amplitude.

It is known from laboratory work that dark opaque rocks and other substances polarize light more or less completely at certain phase angles. Light-colored rocks and materials into which light can penetrate even for short distances and be reflected polarize light relatively little.

As an interesting side light it may be mentioned that Lyot finds the polarization of the moon, Mercury, and the asteroid Vesta to be essentially the same. Since, in all probability, we cannot assume that Vesta is covered with volcanic ash, it seems likely that there are considerable quantities of meteoritic dust and associated fragmental materials on this tiny body.

Parallel to the measurements which have been made on polarization effects are the determinations of temperature variations on the moon from the amount of heat it radiates. This problem is an extremely complex one, for it involves the elimination of reflected light, the proper calibration of the heat-receiving instruments used, and the measurement of the lunar radiant energy. Because of the lack of a dense atmosphere, it is clear that wide temperature ranges over the moon's surface are to be expected as a function of the altitude of the sun.

Lord Rosse, with his large reflector, was the first to make a serious effort in this direction. He found that the lunar equator, three days after full moon, showed a range of temperatures from 200° C. (392° F.) to 75° C. (167° F.). As these values are systematically high, it is probable that he did not succeed in completely separating the reflected and the radiant light.

Langley later denied these results, finding that the surface temperature never rose above freezing, while it often dropped to −200° C. (−328° F.). Peals, and later Fauth, claimed that this was so because there was no lunar atmosphere and hence there could be no storing-up of heat, it would immediately be reflected or reradiated into space. That this point of view is erroneous is clear; for, when the black-body laws are applied, it is found that a perfect black body at the moon's mean distance from the sun would have an average temperature of +4° C. (39° F.).

Verey, at Allegheny, found that, when the sun was up 15° the temperature had risen to 0° C. (32° F.), and when it was vertical, the temperature was at the boiling-point, 100° C. (212° F.). Later in the lunar afternoon it went still higher.

Pettit and Nicholson (15), working with a vacuum thermocouple on the 100-inch telescope, checked closely Verey's first two values but not the third. They measured the heat at the subsolar point on the full moon to be 134° C. (273° F.). From this point the temperature dropped as the limbs were approached. At 0.5 radius the temperature was measured to be 122° C. (252° F.), at 0.75 radius it was 102° C. (216° F.), at 0.9 radius it was 77° C. (171° F.), while close to the limb it had dropped to about 67° C. (153° F.). When the temperature of the subsolar point was measured at the quarter-phases a surprise resulted, for it was only 81° C. (178° F.). The great roughness of the surface must necessarily account for the difference. Consequently, one must be careful in assigning a unique temperature to any particular place on an airless body. The measured value is an average which depends on the orientation of the surface irregularities toward both sun and earth. Wide ranges, both above and below the measured mean value, would exist at each locale. The average temperature as determined at full moon is higher than the boiling-point, 100° C. (212° F.), over one-eighth of the entire lunar surface, an area 1,600 miles in diameter. Yet even under a noonday sun a rock placed in a shadow would soon drop over 200° C. in temperature.

At the eclipse of June 14, 1927, Pettit (16) obtained much extremely valuable information. At a point only 2′ from the south limb, which was the point crossed by the greatest chord of the earth's shadow, the changes of temperature were measured as a function of time throughout the eclipse. The temperature was 69° C. (156° F.) before the eclipse. It dropped immediately at the beginning of the partial phase, which lasted one hour, and was −63° C. (−81° F.) at the beginning of totality. The rapid drop continued for another twenty minutes, reaching −103° C. (−156° F.). Thereafter, for the remainder of totality, two hours and twenty minutes, the drop was very slow. The minimum at the end of totality was −121° C. (−186° F.). For twenty minutes during the first part of the partial phase the temperature did not greatly change, rising to only −113° C. (−171° F.), but thereafter it rose rapidly, attaining 57° C. (135° F.) in the next half-hour.

Epstein's (17) analysis of these variations indicates that the lunar surface materials are exceedingly good insulators or, conversely, have a small heat capacity and therefore cannot be massive materials like granite or limestone but must be light substances like pumice, volcanic ash, or other

Number	Quadrant	Name	Number	Quadrant	Name
1	4	Abenezra	56	3	Campanus
2	4	Abulfeda	57	2	(Cape) Laplace
3	4	Adams	58	4	Capella
4	3	Agatharchides	59	3	Capuanus
5	1	Agrippa	60	2	Cardanus
6	4	Airy Randkrater	61	2	Carlini
7	4	Albategnius	62	2	C. Herschel
8	4	Alfraganus	63	3	Casatus
9	4	Aliacensis	64	1	Cassini
10	4	Almanon	65	4	Catherina
11	3	Alpetragius	66	2	Cavalerius
12	3	Alphonsus	67	3	Cavendish
13	2	Anaxagoras	68	4	Censorinus
14	2	Anaximander	69	1	Cepheus
15	2	Anaximines	70	1	C. Mayer
16	4	Apianus	71	3	Cichus
17	1	Apollonius	72	4	Clairaut
18	1	Arago	73	3	Clavius
19	1	Aratus	74	3	Clavius D
20	2	Archimedes	75	1	Cleomedes
21	1	Archytas	76	4	Colombo
22	2	Aristarchus	77	2	Condamine
23	1	Aristillus	78	1	Condorcet
24	1	Aristoteles	79	1	Conon
25	3	Arzachel	80	4	Cook
26	1	Atlas	81	2	Copernicus
27	1	Autolycus	82	3	Crüger
28	4	Azophi	83	4	Cuvier
29	4	Bacon	84	4	Cyrillus
30	3	Bailly	85	3	Cysatus
31	3	Ball	86	3	Davy
32	4	Barocius	87	1	Dawes
33	3	Bayer	88	4	Delambre
34	4	Beaumont	89	2	Delisle
35	2	Beer	90	1	Democritus
36	2	Beer A	91	1	Dionysius
37	1	Bernouilli	92	2	Diophantus
38	1	Berosus	93	1	Egede
39	1	Bessel	94	2	Encke
40	3	Bettinus	95	1	Endymion
41	2	Bianchini	96	2	Epigenes
42	3	Billy	97	2	Eratosthenes
43	3	Birt	98	3	Euclides
44	3	Blancanus	99	1	Eudoxus
45	2	Bode	100	2	Euler
46	4	Boguslawski	101	4	Fabricius
47	3	Bonpland	102	4	Faraday
48	4	Borda	103	4	Faye
49	1	Boscovich	104	4	Fermat
50	3	Bullialdus	105	1	Firmicus
51	1	Burckhardt	106	3	Flamsteed
52	1	Bürg	107	2	Fontenelle
53	4	Busching	108	3	Fourier
54	3	Byrgius	109	4	Fracastorius
55	1	Calippus	110	3	Fra Mauro

Number	Quadrant	Name	Number	Quadrant	Name
111	1	Franklin	166	1	Le Monnier
112	4	Frauenhofer	167	3	Letronne
113	4	Furnerius	168	2	Leverrier
114	2	Galileo	169	4	Licetus
115	2	Gambart	170	4	Lilius
116	3	Gassendi	171	4	Lindenau
117	4	Geber	172	1	Linné
118	1	Geminus	173	1	Littrow
119	4	Gemma Frisius	174	3	Longomontanus
120	4	Goclenius	175	4	Lubbock
121	1	Godin	176	4	Maclure
122	3	Grimaldi	177	1	Macrobius
123	1	Grove	178	4	Mädler
124	3	Gruemberger	179	4	Magelhaens
125	3	Guericke	180	3	Maginus
126	4	Guttemberg	181	2	Mairan
127	1	Hahn	182	1	Manilius
128	3	Hainzel	183	1	Manners
129	4	Halley	184	4	Manzinus
130	3	Hansteen	185	2	Marco Polo
131	2	Harpalus	186	2	Marius
132	4	Hase	187	1	Mason
133	3	Heinsius	188	4	Maurolycus
134	2	Helicon	189	1	Menelaus
135	1	Hercules	190	3	Mercator
136	2	Herodotus	191	1	Mercurius
137	3	Herschel	192	3	Mersenius
138	3	Hesiodus	193	1	Messala
139	2	Hevel	194	4	Messier
140	4	Hind	195	4	Messier A
141	3	Hippalus	196	4	Metius
142	4	Hipparchus	197	2	Milichius
143	4	Hommel	198	3	Miller
144	4	Horrocks	199	3	Miller A
145	2	Hortensius	200	3	Moretus
146	1	Hyginus	201	3	Mösting
147	4	Hypatia	202	3	Mösting A
148	3	Inghirami	203	4	Mutus
149	4	Isidorus	204	3	Nasireddin
150	4	Jacobi	205	4	Neander
151	1	Jansen	206	4	Nearchus
152	4	Janssen	207	1	Neper
153	1	Julius Caesar	208	1	Newcomb
154	4	Kant	209	3	Newton
155	2	Kepler	210	3	Nicollet
156	3	Kies	211	2	Olbers
157	2	Kirch	212	3	Orontius
158	3	Kircher	213	3	Parry
159	2	Kunowsky	214	4	Pentland
160	4	Lacaille	215	4	Petavius
161	3	Lalande	216	2	Philolaus
162	2	Lambert	217	3	Phocylides
163	3	Landsberg	218	2	Piazzi Smyth
164	4	Langrenus	219	1	Picard
165	4	Legendre	220	4	Piccolomini

Number	Quadrant	Name	Number	Quadrant	Name
221	3	Pictet	265	4	Snellius
222	1	Pierce	266	2	Sömmering
223	3	Pitatus	267	1	Sosigenes
224	4	Pitiscus	268	2	Stadius
225	2	Plato	269	4	Steinheil
226	4	Playfair	270	4	Steinheil A
227	1	Plinius	271	4	Stevinus
228	4	Pontecoulant	272	4	Stiborius
229	1	Posidonius	273	4	Stoflerus
230	1	Proclus	274	1	Strabo
231	3	Ptolemaeus	275	4	Tacitus
232	3	Purbach	276	1	Taquet
233	2	Pytheas	277	1	Taruntius
234	2	Pythagoras	278	4	Taylor
235	3	Ramsden	279	1	Theatatus
236	4	Reichenbach	280	3	Thebit
237	3	Regiomontanus	281	3	Thebit A
238	2	Reiner	282	4	Theophilus
239	2	Reinhold	283	2	Timaeus
240	4	Rheita	284	2	Timocharis
241	3	Riccioli	285	2	T. Mayer
242	1	Ritter	286	1	Tralles
243	1	Römer	287	1	Triesnecker
244	4	Rosenberger	288	3	Tycho
245	1	Ross	289	1	Ukert
246	3	Rost	290	3	Unnamed
247	1	Sabine	291	4	Vega
248	4	Sacrobosco	292	4	Vendelinus
249	4	Santbech	293	3	Vieta
250	3	Saussure	294	3	Vitello
251	3	Scheiner	295	1	Vitruvius
252	2	Schiaparelli	296	4	Vlacq
253	3	Schickard	297	4	Walter
254	3	Schiller	298	3	Wargentin
255	4	Schomberger	299	4	Webb
256	2	Schröter	300	4	Werner
257	1	Schumacher	301	4	W. Humboldt
258	1	Scoresby	302	3	Wilhelm I
259	3	Segner	303	4	Wrottesley
260	2	Seleucus	304	3	Wurzelbauer
261	2	Sharp	305	4	Zach
262	3	Short	306	3	Zuchius
263	4	Simpelius	307	4	Zagut
264	3	Sirsalis			

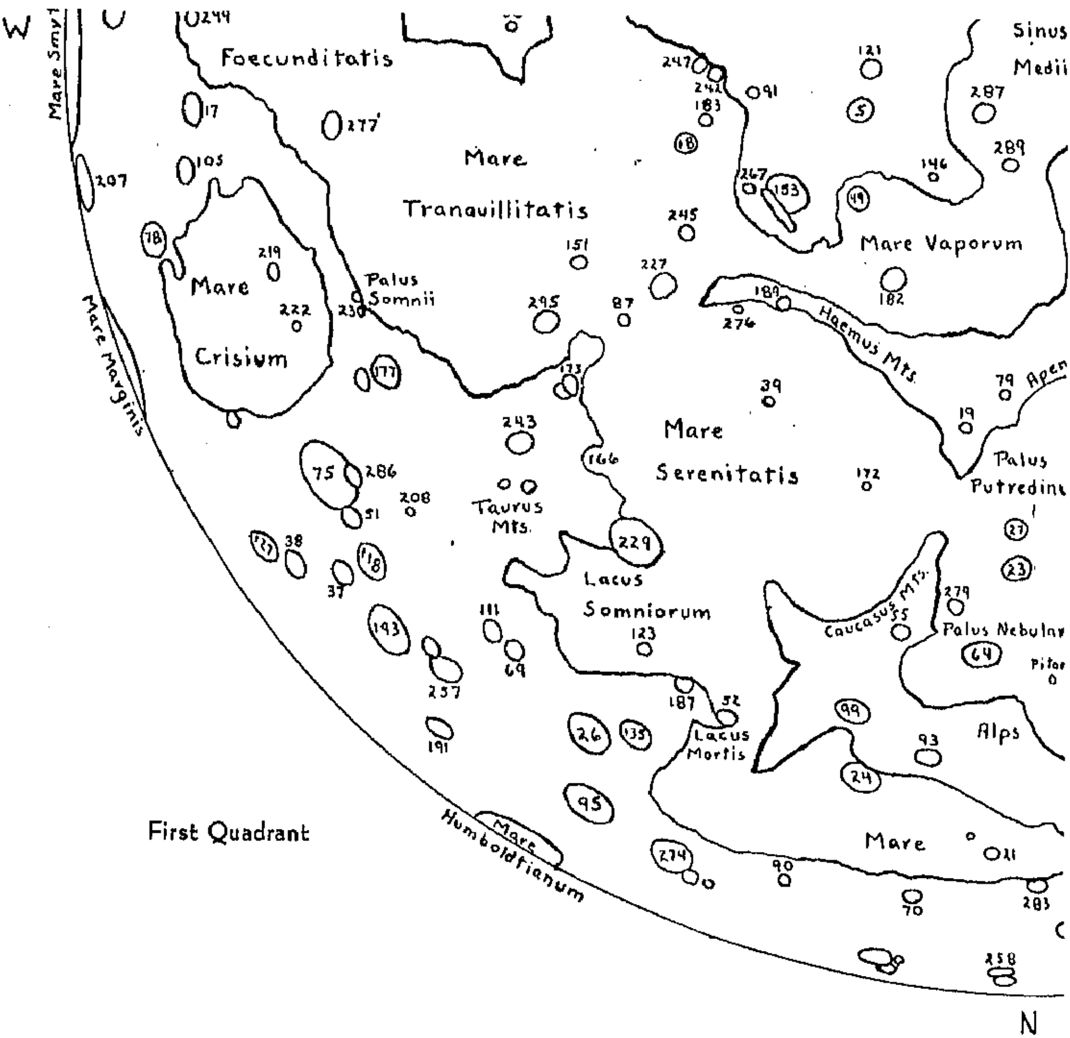


FIG. 2.—Map of the moon, Quadrant 1

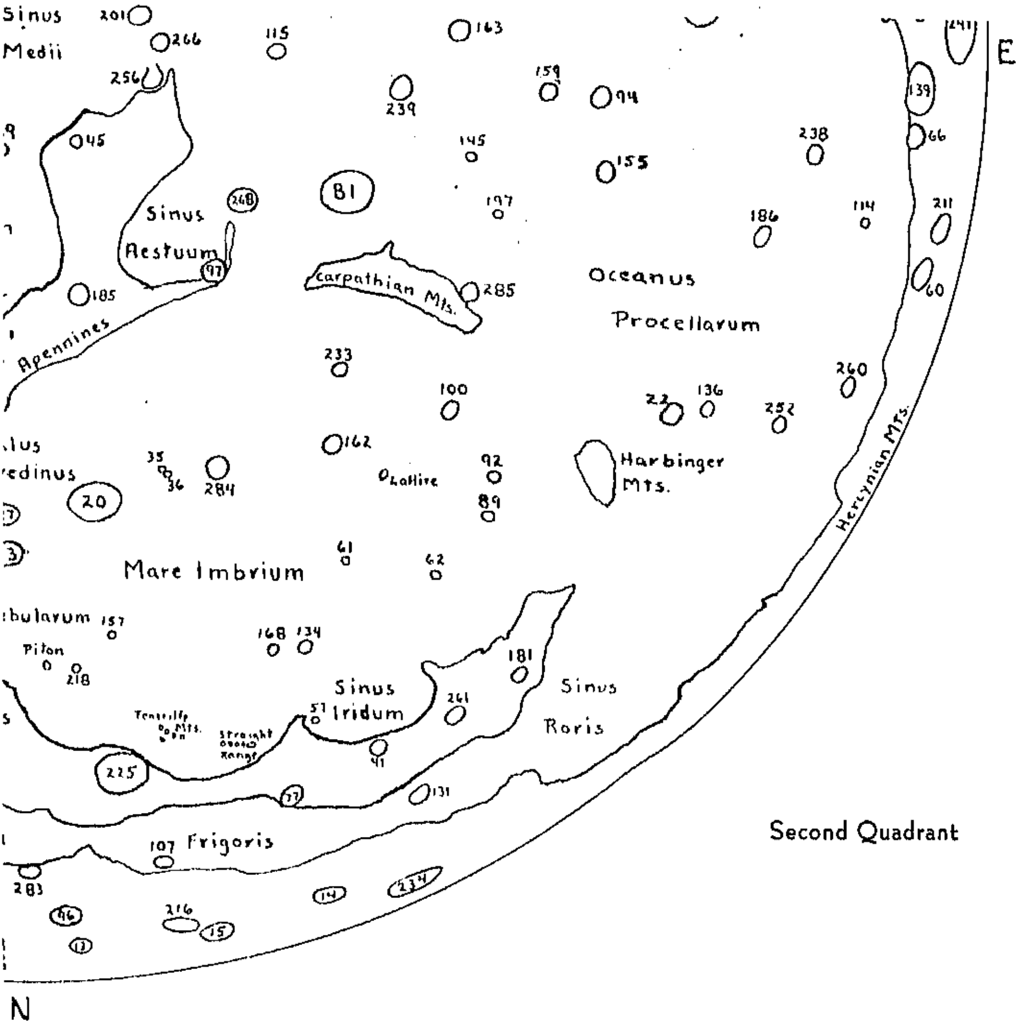


FIG. 3.—Map of the moon, Quadrant 2

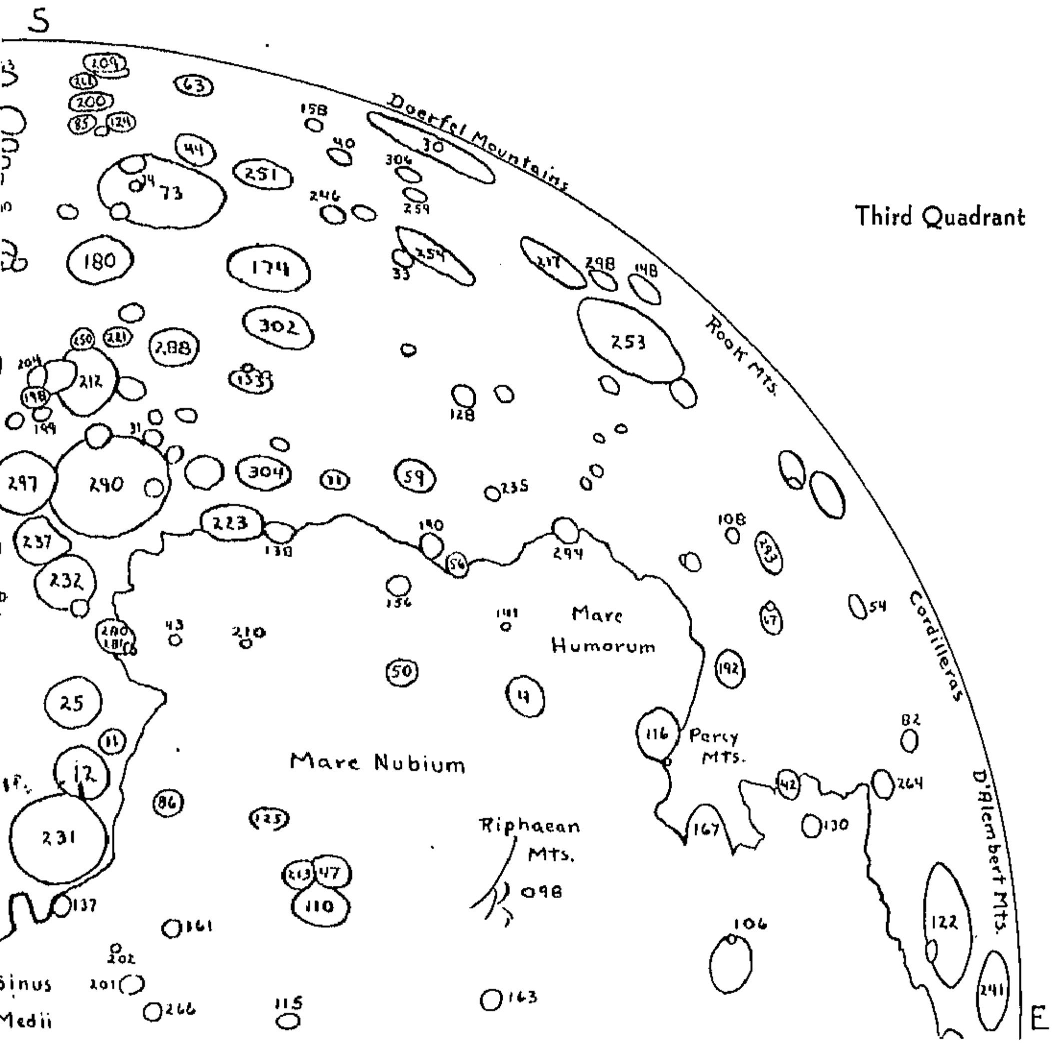


FIG. 4.—Map of the moon, Quadrant 3

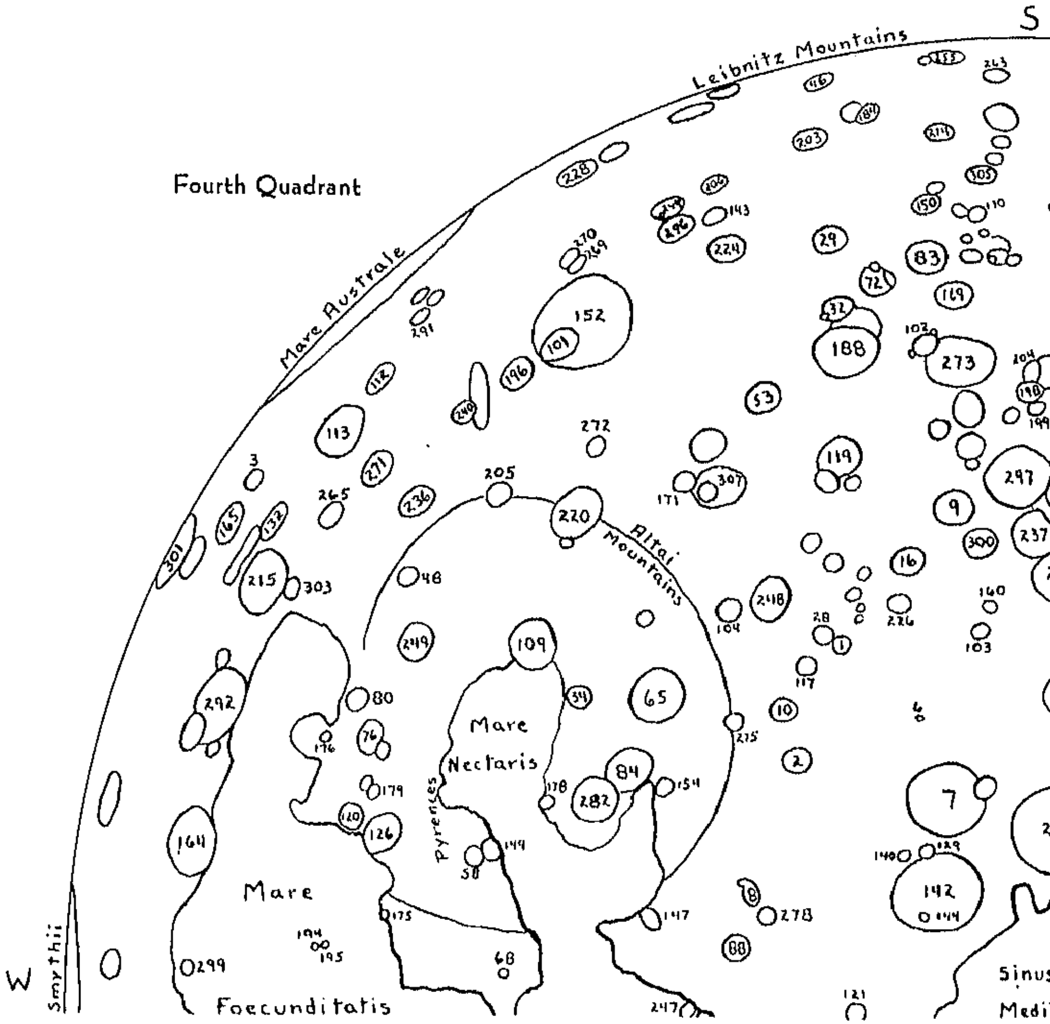


FIG. 5.—Map of the moon, Quadrant 4

dustlike or porous materials. This interpretation is in good agreement with measures of polarization and surface brightness in demonstrating that the moon's surface is very rough and broken up, with large quantities of dust or fine particles spread over the ground.

The temperature of the surface during the eclipse did not fall as low as Pettit and Nicholson have found for the dark side. During the long lunar night the temperature is fairly constant at −153° C. (−243° F.).

R. W. Wood (18), while studying the moon in the ultraviolet region of the spectrum, found a "black desert" east of the crater Aristarchus. This area appeared quite dark when photographed in light of λ 3100–3250 A, was still conspicuous in violet light, and was even faintly visible as a shaded patch to the naked eye, but photographs taken in yellow light did not reveal it. Keenan found it to be 20 per cent stronger in infrared light than in the ultraviolet. Wood felt that the color curve of this region seemed to coincide closely with that of a rock which had been previously exposed to sulphur fumes. No such appearance was found in any crater, and hence sulphur, which is often found associated with terrestrial volcanoes, is missing, or at least extremely rare, around the lunar craters.

It is not pretended that these paragraphs constitute a complete history of the development of lunar knowledge. Instead, certain high points have been emphasized, particularly as they bear on the problems of determining the nature of the moon and the general physical conditions of the lunar surface and body. Countless hours have been spent by hundreds of astronomers, mathematicians, geologists, geophysicists, chemists, physicists, and others in investigating the earth's nearest neighbor. These cannot be acknowledged in a volume of this size and their omission signifies no slight. Where such contributions pertain to subjects discussed in other sections, they are recognized.

The points which have been discussed do give, however, a rather complete general picture of the state of things on the moon's surface. It remains to demonstrate the various processes and mechanisms which have operated on the moon to bring it to its present condition.

CHAPTER 2

Surface Features

IT IS the purpose of this descriptive chapter to outline the major sequences, similarities, and differences among the lunar surface structure phyla in order that general laws, progressions, and correlations may be established. When this is done, and only then, it will be possible to describe the basic processes by which these features came into being.

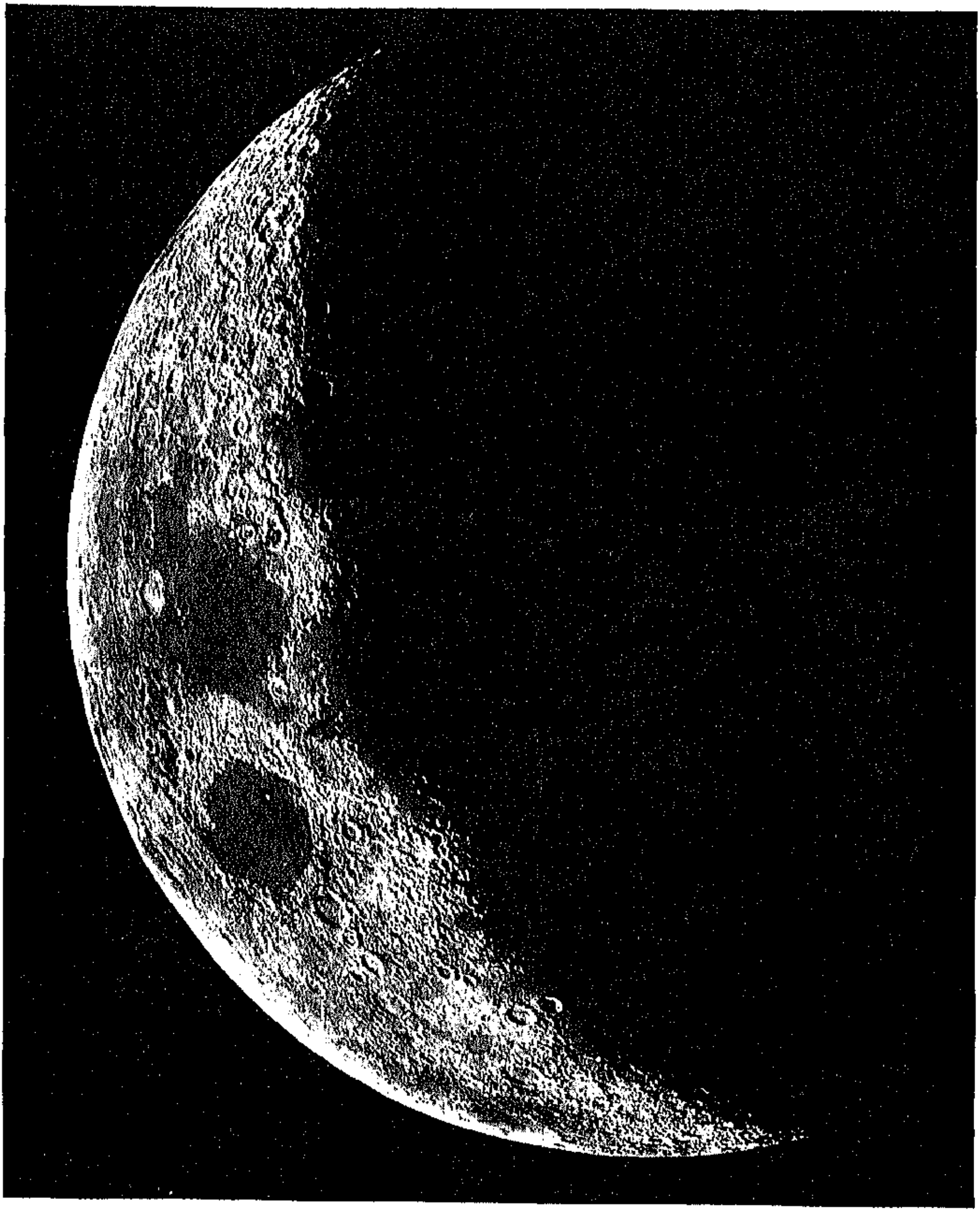
There are no duplicate objects on the moon. No two structures are exactly alike. In each of the major types there is a relatively well-defined sequence where the change of characteristics is related to size. Nevertheless, it has been the general practice to subdivide the various groups of formations into more or less independent families and to discuss each by itself.

As an example, the sequence of craters is often partitioned in this manner. The smallest craters visible are usually called "craterlets" or "craterpits." As the size increases, the simple term "crater" is applied; still larger objects are named "crater rings," then "mountain-ringed plains" or "bulwark plains," and, lastly, the great "mountain-walled enclosures," some of which are really small seas. The term "seas" is used here in lunar nomenclature to mean an extended lava flow.

It is one of the theses of this volume that there is no fundamental difference between the nature of small and large craters. They were formed in similar manners, the larger crater simply resulting from a greater application of power. The superficial differences between craters thus are due to local conditions at the time of origin, to changes which have occurred later, and to systematic effects which are functions of the magnitude of the crater-forming effort.

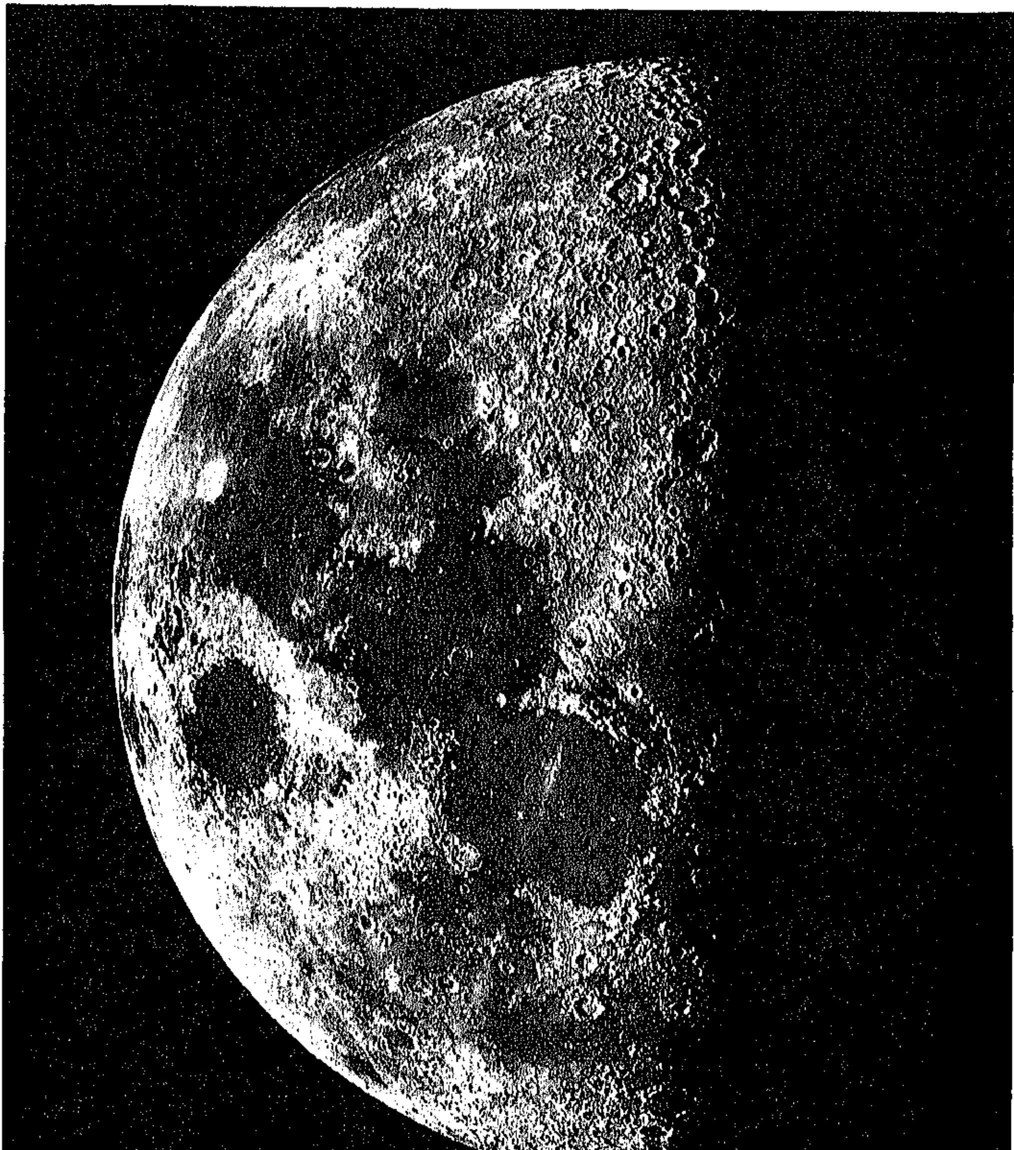
A casual glance at a photograph shows that there are wide differences in the ages of various craters. Many seem to be perfect, unmarred by other craters formed subsequently. Some have been so badly damaged as to be almost unrecognizable. It is believed, with reason, that the less-disturbed

PLATE I



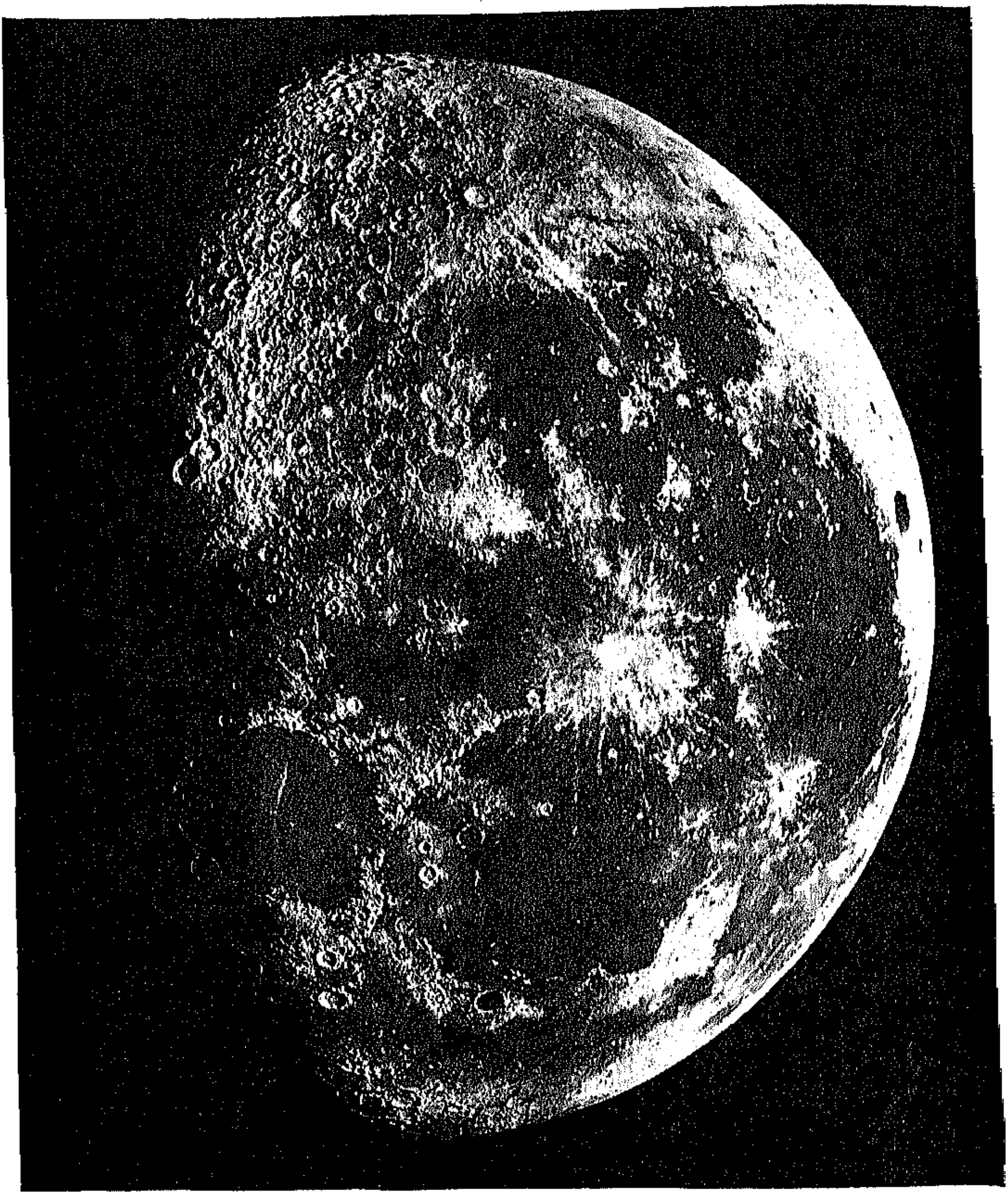
Moon, Age 4.6 Days, June 2, 1938 (Lick Observatory)

PLATE II



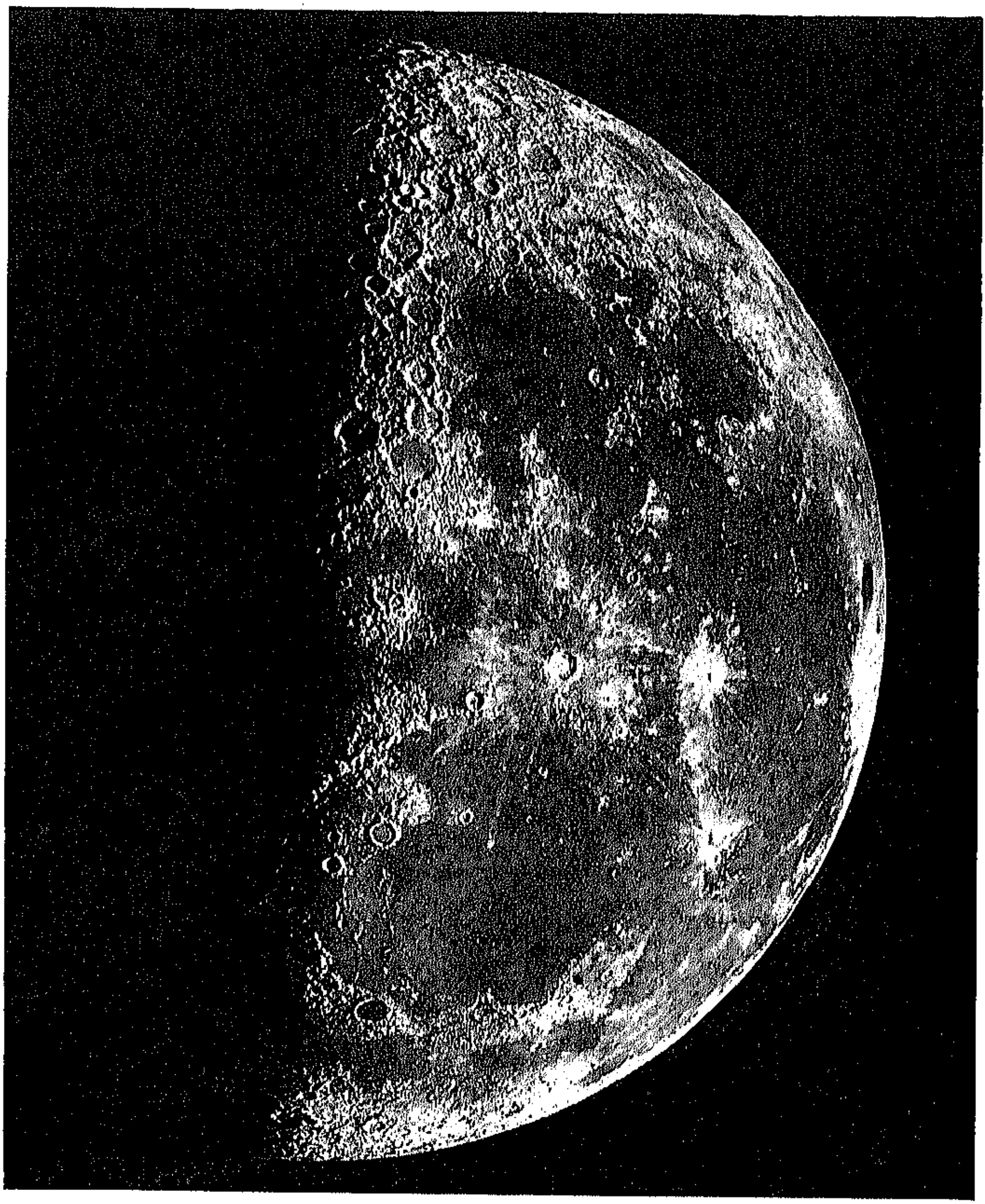
Moon, Age 7 Days, May 6, 1938 (Lick Observatory)

PLATE III



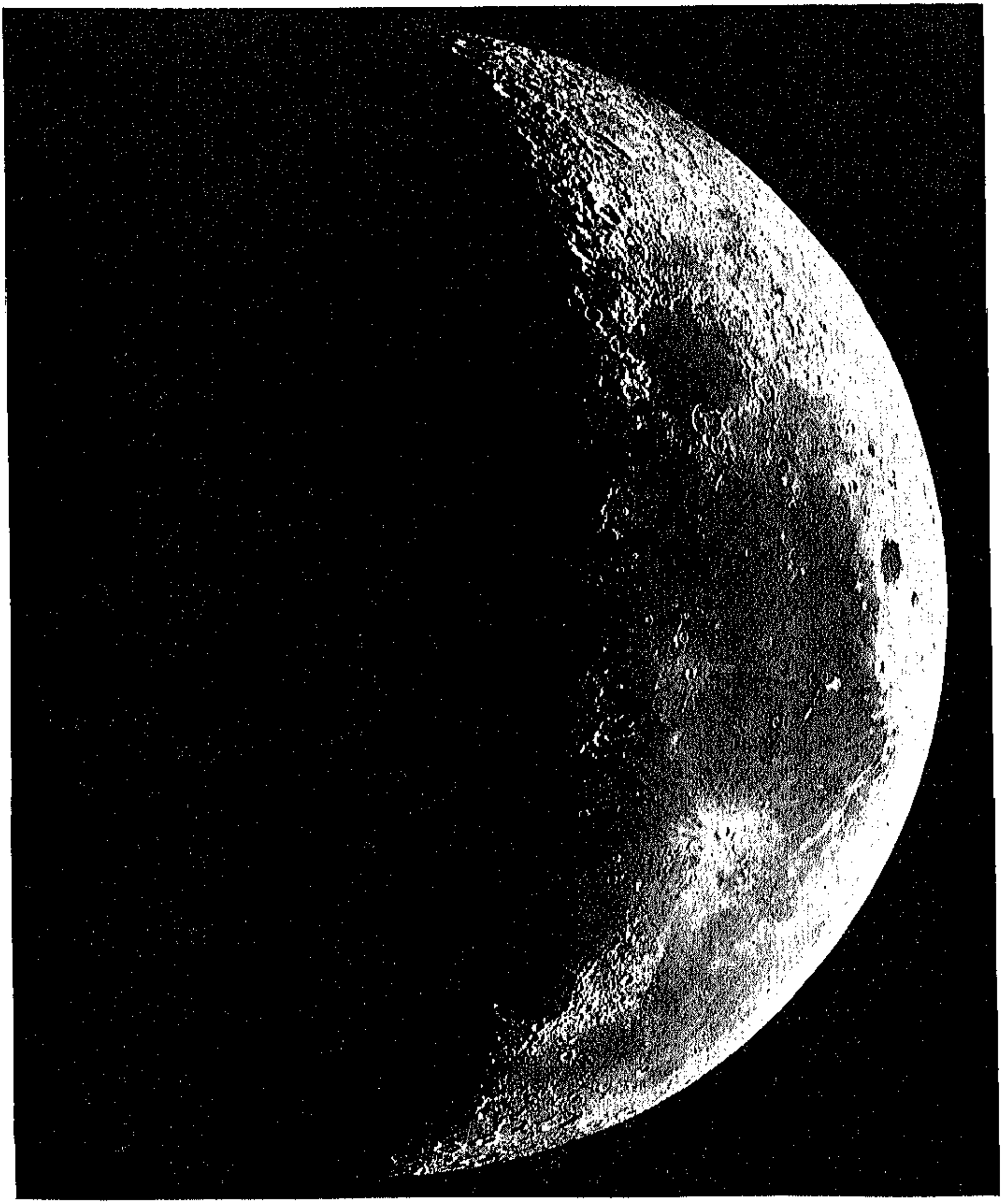
MOON, AGE 20.04 DAYS, OCTOBER 24, 1937 (LICK OBSERVATORY)

PLATE IV



Moon, Age 22.06 Days, October 26, 1937 (Lick Observatory)

PLATE V



Moon, Age 24.3 Days, August 20, 1938 (Lick Observatory)

and better-defined craters are most nearly representative of craters as they were when formed.

Properly to evaluate the real sequence of crater types, it is necessary to describe representative examples covering the gamut of sizes, thus correlating the systematic variations.

At the limit of telescopic vision are many thousands or even hundreds of thousands of tiny craters. An earthling, seeing such a pit at close hand, would be impressed by its vastness, but distance dulls the sharp details and leaves only a tiny pinprick in the lunar skin. The angle of illumination causes strange optical effects. Many of these small craters appear only as black spots under a moderately high sun; the structure vanishes and the interior shadow remains. Possibly a bright crescent marks the sunlit wall. As the terminator is approached, the crater details become more easily visible, the shadow broadens, and the exterior rim appears. Still nearer, the interior becomes buried in night while the raised rim turns into two opposing, dissimilar crescents. Close to the terminator these tiny craterlets seem to grow in height, though not in diameter. It is an effect of contrast, irradiation. As a result, the appearance of a small volcanic cone is simulated briefly. Measurements show, and the appearance of these pits at other phases indicates, that they do not have high rims in proportion to their diameters. They are simple craterpits and are found by myriads profusely scattered over all parts of the surface.

Each of these little craters is a cup with steep inside slopes gradually decreasing to a nearly level interior depressed beneath the true ground level. They are too small to permit discovery of a central peak, but the existence of small central elevations is not thereby denied. The crater outlines are generally circular while the rim is smoothly symmetrical, rising but little from the plain and dropping outward gradually to its level. The volume of the rim is equal to the volume of the subsurface portion of the crater (Table 7, chap. 7), although mere inspection would lead to other conclusions. The rim rises to a maximum height on its inside edge but gives no indications of any landslides on the steep inner wall. The lack of irregular detail is undoubtedly due to the small apparent size of the crater and the blurring effects of the earth's atmosphere.

A typical example is about 20 miles west of Piazzi Smyth. This tiny crater is 1.3 miles in diameter, 1,240 feet deep, with a rim raised 300 feet above the mare. The nearest terrestrial counterpart is the great Arizona

Meteorite Crater whose dimensions are approximately one-half those of this lunar crater.

One step larger than this nameless little pit is the neighboring Piazzi Smyth, 6 miles in diameter, 3,500 feet deep, with a 2,100 foot-high (maximum) rim. A crater of this size is only $5''$ of arc in diameter; it is not surprising that it is difficult to detect much of the fine structure. Traces of irregularities appear in the outer rim as if the crater-forming force had ejected matter in lumps in a not quite uniform manner. No central peak has been found. The major difference between Piazzi Smyth and its neighbor, other than size, is that the smaller pit is relatively deeper.

Clearly displayed on the wide expanse of Mare Serenitatis is Bessel. Schmidt (8) gives its diameter as 12 miles, but 10 would be a better figure. The depth is 4,300 feet, and the rim is 1,600 feet high.[1] Mädler (19) found no central peak, but Webb (20) claimed to have seen one on two separate occasions. A photograph taken at Lick Observatory on May 6, 1938, definitely shows an irregular shadow across the crater floor, but whether this is due to a central peak or to a minor gap in the west wall is uncertain.

A portion of the bright ray from Tycho (or Menelaus) may be seen crossing the northeastern floor. The walls appear single, much as do those of Piazzi Smyth, and the interior smoothly rounded. Bessel is relatively more shallow than smaller craters. The ratios, depth over diameter, for the three craters so far described are $\frac{1}{6}$, $\frac{1}{9}$, and $\frac{1}{12}$, respectively. This ratio continues to decrease as the absolute size of the craters increases until a value of nearly $\frac{1}{50}$ is found for the largest normal craters. Similarly, the rim height slowly increases.

Conon is located in the jagged uplands of the Apennines, a beautiful little crater, 15 miles in diameter and 6,400 feet deep. It possesses a small central elevation. The walls lack the smooth symmetry of those similar craters found in the plains areas. Quite obviously the form of Conon was determined by its heredity and conditioned by its environment. The rim is bulged inward just where it comes in contact with a mountain arm. No evidences of landslips or multiple walls are to be seen.

1. The variations in measured lunar crater dimensions are due to two factors. These data have been gathered largely by observers using small telescopes; the normal accidental errors are thus rather large. Blended with this artificial scatter are small but real variations in rim heights and crater depths relative to diameters. Although the two effects cannot now be completely separated, the use of averages based on intercomparisons of many craters is on a firm foundation.

On the floor of mighty Clavius lies Clavius D, the same diameter as Conon, 6,000 feet deep, with a rim jutting up 3,100 feet. It has a small but definite central peak, which, like all peaks in lunar craters, does not rise to the plane of the outer ground level. Here the rim clearly is irregular in height, while the outer slopes show valleys and hills which closely resemble those to be seen correspondingly from airplane views of the Arizona Meteorite Crater. Part way down the inner wall is the bare suggestion of a landslip or terrace, visible all the way around the crater at about the normal ground-level. This is the first appearance of this characteristic, so prominent at many larger craters.

It is important to note that these fine details disappear on poor photographs and that the appearance of Clavius D then reverts to one much like that of Piazzi Smyth.

On the edge of Mare Nectaris and dwarfed by its giant neighbor, Theophilus, is a magnificent crater, Mädler, whose name honors one of the greatest students of the moon. Mädler is 20 miles in diameter, 7,500 feet deep, and has a rim rising 3,600 feet above the plain. The central elevation is easily seen and is found to have one major peak and others subsidiary to it. The inner wall of the crater has a well-defined ridge running around it at some distance below the main rim. It is an exaggeration of the condition noted at Clavius D. In Mädler and all larger pits the rim heights are jagged, their outlines almost, but not quite, circular. Some cases are known which tend toward polygonization.

Here is clear evidence that explosive activity occurred, for Mädler has ejected light-colored, finely divided matter, primarily to the southwest onto Mare Nectaris. There are bare traces of ribs radiating from and part of the outer rim and indications of the coarse ejectamenta surrounding the main structure.

From Mädler we progress naturally to Autolycus, 24 miles in diameter, 9,500 feet deep, whose rim rises 4,800 feet. It shows a small central peak. In other respects Autolycus simply amplifies the features found at Mädler. The rim is more irregular in height, and the inner wall ridge is more pronounced. On all sides radiate hill chains and short ridges on to the plains. Some markings, even as far as 75 miles from the center of the crater, can be seen to be valleys with slightly raised edges. These valleys are radial to Autolycus and hence must have been formed by or associated with the crater-forming process. The entire outer rim is a bed of coarse blocks and

angular fragments. The composition of the rim materials is becoming evident. Sired by Autolycus is a ray system extending in all directions. Some of its rays even mark the floor of Archimedes.

Manilius, 25 miles in diameter, 7,700 feet deep, with a 3,000-foot-high parapet, is almost a counterpart of Autolycus. It has a multiple central mountain and is situated nearly centrally in a bright nimbus of diffuse rays. The serrated rim is double, the inner ridge lying lower than the main edge. Surrounding the crater is the zone of incoherent masses, and there are radiating ridges and valleys in abundance.

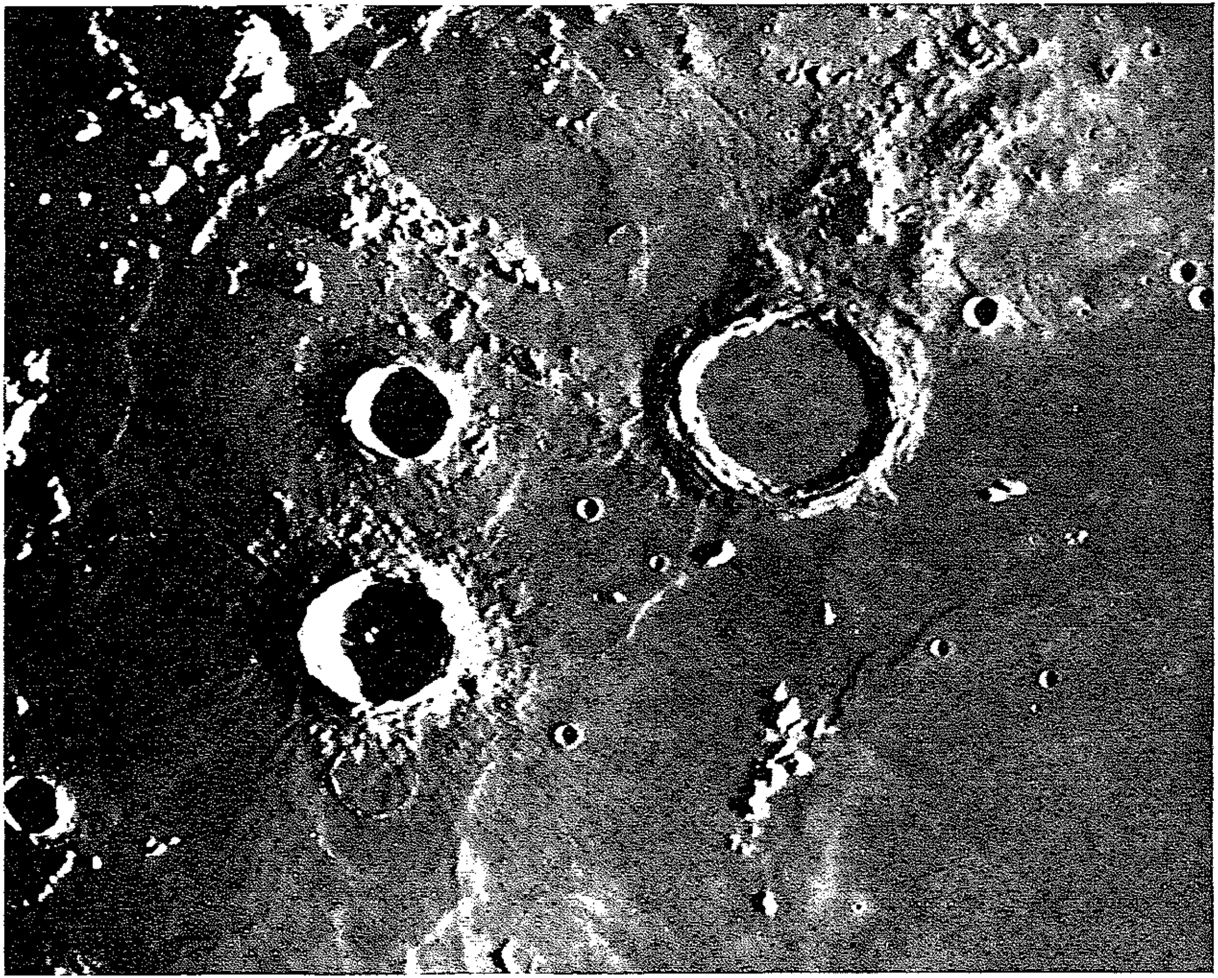
Alpetragius, 26 miles in diameter, 9,000 feet deep, with a rim 3,300 feet high, is a somewhat variant form of crater. The radiating ridges and valleys are present, particularly on the southeast, but are not prominent. There are no associated rays. The inner terrace is easily seen but is less well developed than in many other craters of similar size. Alpetragius' main claim to fame is a vast low central mountain, much larger than is normal for such a crater. On this elevation is a small crater.

In many ways the most beautiful crater on the moon is Aristillus. Of intermediate size, 35 miles in diameter, 10,300 feet deep, and possessing a raised rim 4,400 feet high, Aristillus is magnificently placed in a focus of the mountainous curve of the Alps, Caucasus, and Apennine ranges. The floor of the surrounding Mare Imbrium, or, as it is locally known, Palus Nebularum, is smooth, with only occasional low ridges to mar it. Broadcast over this area is a great system of rays extending as far as Plato. Over a circular area 200 miles in diameter lie uncounted grooves and ridges, all radial to the crater. The existence and direction of the shadows prove that the grooves are sunken into the plain. Many of the valley-like grooves have cut completely through the ring of a partially buried crater north of Aristillus or through low scattered ridges, particularly southwest of the crater. Hence it must be inferred that these grooves were actually gouged out of the solid crust by some process associated with Aristillus and do not represent graben or downfaulted blocks of the crust.

The usual zone of breccia is well developed, while the inner walls of the crater show three main terraces whose lines of demarcation are not as clearly defined as at smaller craters. The central floor is occupied by a great mountainous complex composed of irregular blocks.

About 500 miles to the southeast lies Eratosthenes, only 2 miles broader than and equal in depth to Aristillus. Its rim has been measured as 3,300

PLATE VI



feet high. In their main features the two craters practically duplicate each other. If a ray system surrounds Eratosthenes, it is very weak. The major difference, however, is the condition of the interior walls of Eratosthenes, which exhibit a chaotic series of terraces, none of which extends completely around the crater. The type of structure which appeared so inauspiciously at Clavius D now has reached full development. At larger craters the terraces differ only in detail.

As the craters grow larger, little further change occurs. In the great southern uplands lies Tycho, called by Webb the metropolitan crater of the moon. Its diameter is 54 miles, depth 12,000 feet, and its rim height is given as 7,900 feet. The last value is probably too great. Tycho is a magnificent sight at all times. The central elevation is actually complex although there is only one pre-eminent peak. The floor is never smooth, and the inner walls rise in as many as five terraces to a well-defined crest which then descends toward the outside in massive terraces and buttresses. The latter are logical developments from the formations glimpsed on the irregular external slopes of Clavius D.

All the formations closely surrounding Tycho have an indistinct appearance caused by the combined effects of thousands of tiny craters, crater-like formations, and radial ridges and grooves. Quite certainly these structures were by-products of the birth agonies of the main crater.

The great ray system, which is even visible to the naked eye, is well known. Some of these streaks can be traced well over 1,000 miles.

Second only to Tycho in the extent and diversity of its ray system is Copernicus. Larger than Tycho, 56 miles in diameter, 11,000 feet deep, 3,300 feet high, Copernicus differs in minor ways. Its location on the lava flow of Mare Nubium shows off the buttresses, ridges, terraces, and other structures of the outer wall to better advantage. The radiating marks are very prominent, and many examples are to be found in which such valleys cut through near-by upraised formations. The central peak is multiple with the components widely separated, and the floor appears to be level, as if it had once contained a small amount of liquid which later froze in position. The inner wall terraces defy description in their complexity and appear to have encroached farther on the rim than is usual.

Theophilus is an enlarged version of Tycho and Copernicus. It is 65 miles in diameter, 14,400 feet deep, and has an outer wall height of 3,800 feet. All the previously described characteristics may be found here includ-

ing a weak but well-defined ray system extending over much of Mare Tranquillitatis and Mare Nectaris.

The importance of Theophilus in this sequence is not so much its own physical details but the fact that it was formed subsequent to another crater, Cyrillus, of almost equal size, and now overlaps the older formation. In the region of overlap Theophilus appears to be perfectly normal, while that portion of Cyrillus has disappeared. This is typical of the few cases where two nearly equal craters overlap. The newer of the two takes its form from its own available energies; the older is partially destroyed.

Near the west limb lies the beautiful crater Langrenus, an object which would be far more famous were it more favorably placed. It is 81 miles in diameter, 13,300 feet deep, and 2,600 feet high. Langrenus also shows the terraced interior and buttressed exterior, with the surrounding radial markings. A ray system speckles much of Mare Foecunditatis. The central mountain is complex. Except for its size, it is similar to Theophilus and offers no new features. With the possible exception of Newton, Langrenus is the largest crater on the visible surface of the moon which has not undergone serious modification by craters formed later or by other forces.

None of the largest craters is in its pristine condition. Maginus offers a typical example. It is 118 miles in diameter, 14,800 feet deep. The height of the rim is very difficult to measure owing to the irregular nature of the surrounding region.

No rays or surrounding radial marks are to be found. From the age of the crater and the adjacent complex they perhaps are not to be expected. It is noticed that not all craters show rays. However, a crater is far more likely to possess them if it is a clean, new-looking structure than if it is old and battered.

The central mountain shows several peaks, but none is prominent relative to the size of the crater. The inner walls are extremely irregular, while the outer slope is made up of vast buttresses.

The same description fits Clavius equally well. This great object, largest of the normal craters on the moon, is 146 miles in diameter, 16,100 feet deep, and 5,400 feet high on the exterior. Its radiating buttresses form almost a circular mountain range.

In the cases of Maginus, Clavius, and numerous others of the large but old-appearing craters, the floors are nearly flat, the central mountain is not prominent, and the depths are not as great relative to the diameters as

one would be led to expect from the trends in the smaller but newer-looking craters. It seems as though some force has acted to cause the older craters to become more and more shallow than they were originally. Immediately east of Walter is a tremendous, yet nameless, crater, 139 miles in diameter. It is ancient of days and has suffered numerous smaller superficial craters to develop at many points. Walter has destroyed fully one-eighth of its rim. Nevertheless, there is nothing visible among these secondary actions which would account for the extreme shallowness of the unnamed crater. Some other mechanism must be called upon to account for this widespread phenomenon.

The craters may also be changed in appearance by a third method. Many of the pits have dark interiors closely resembling the tone of the maria. Usually it is found that such objects are much shallower than is normal among the newer forms and that their floors are strangely level. The incidence of central mountain peaks is markedly lower in this group of craters than in all other classes. It is evident that by some means the lavas of the maria or associated lavas have seeped into many of the near-by craters and formed stagnant pools which later solidified. The broad crater Ptolemaeus, close to the center of the disk, demonstrates clearly its lava-filled nature.

There is still another way by which the lunar craters are modified in appearance. With rare exceptions the craters lying on the borders of the maria are lower on the side toward the sea. A notable example of this effect is another vast, nameless crater east of and encompassing Thebit. The western side is rather well defined. In the north it is marked by the Promontory Aenarium reaching into Mare Nubium. On the east a curved line of wrinkles in the mare marks the submerged rim. The included Straight Wall aids in this effect. Immediately north is another crater of almost identical size and condition. The eastern rim seems to be outlined by a change in the brightness of Mare Nubium.

One of the most important facts concerning the craters of the moon is their peculiar distribution. Numerous studies have shown, and indeed it is apparent to the eye, that except for the modifications produced by the great overflowing lava sheets the craters are distributed essentially at random. This observed condition must be explained by any acceptable theory of the origin of the moon's surface features. It is in sharp contrast

to the well-defined zonal distribution of past and present volcanoes on the earth.

The great sheets of molten rock which cover about 40 per cent of the visible surface came into being at almost the end of the period of crater formation. Thousands of craters of postmare age may be found scattered at random over the gray seas, but their frequency is far lower than is customary in the upland regions. This observation does not date the lava flows with respect to the age of the moon; it merely serves to place them properly in a relative temporal sequence.

One class of crater-like formation must be segregated from the normal groups of craters. These are the so-called "chain" craters. Many times they are found lined up like post holes dug for a fence. In some cases they are actually contiguous; in others they are connected by easily seen clefts or rills.[2] The most prominent group of chain craters runs north-south midway between Eratosthenes and Copernicus. At the northern end of the line the individual craters begin to merge until they almost take on the appearance of a normal rill extending out into Mare Imbrium.

Running from Davy almost to Ptolemaeus is a rill which shows at least six crater-like structures centered on it. A similar formation lies east of Archimedes, and a great many other examples could be cited.

In Alphonsus, which is partially filled with lava, there are five darker spots. In each of these cases there is a small crater in the dark spot, and in four of the five regions the crater has developed on a rill.

Craters of these types rarely, if ever, show raised rims and are thus set aside as a distinct class from the majority of normal craters. There does not seem to be any question but that they are volcanic blowholes of some kind and are directly the products of gases contained in the moon's crust. They may be found on any portion of the surface. Such craters are always small. In all probability craters of this type are not limited to association with rills but may occur often, particularly on the lava flows. A large number, although a small percentage, of the lesser pits may fall into this category.

There is no single case of a group of large craters being joined together by a rill. The law of chance, exemplified by the random distribution of normal craters, would compel certain accidental coincidences of crater and rill, but no systematic alignments of large craters have been found.

2. Does not connote a watery origin.

Although small craterlets are often associated with rills, the latter normally are not marked by frequent craters. The usual rills may be subdivided into two major classes. Near Triesnecker is a large group of short, irregular cracks, very jagged in appearance, which seem to be bottomless In other cases, notably the great Hesiodus cleft, the crack has been nearly filled up by material either oozing up from below or subsiding from above.

Fundamentally the rill is a great crack and thus marks a region which once underwent more than the usual tension. The distribution of rills is especially revealing. They may be found anywhere on the moon, but the primary systems define the borders of the lava flows. Usually they are parallel to the edges of the maria, but a lesser number is perpendicular to them. This is an observation of utmost importance. The rill is not purely a surface phenonenon; its causes are deep-seated. Often such a cleft will split open a crater or mountain without an appreciable deviation in its course as if it did not exist. Tremendous forces must have been operating. Often small rills are found within lava-filled craters. Petavius, Pitatus, Alphonsus, and Gassendi offer many type cases.

The maria fall into two classes, those with irregular borders and those bounded by mountains. It is beyond question that the seas were once liquid, for they have overflowed thousands of craters and left only occasional high spots to mark their existence. Most of the maria join to Mare Imbrium, the largest of the mountain-bordered plains.

In every case the great lava flows are depressed regions, often lying thousands of feet lower than their surroundings. Whenever the border is mountainous, the sea is nearly circular and there is an escarpment on the inner wall and a gradual slope down to the normal level on the outer face. The mountain ranges are all found to be concentric with a sea and thus to be composed of a series of circular arcs. This description also applies to the Altai Mountains, which form a small part of a great circle of mountains everywhere parallel to, but not touching, the borders of Mare Nectaris. Mountains like the Liebnitz or Doerfel ranges on the limbs cannot be so classified, although Molesworth found the appearance of the latter suggestive of an immense ring plain seen in profile.

Among the mountain-bordered seas are Mare Imbrium, Mare Serenitatis, Mare Crisium, Mare Nectaris, Mare Humorum, Mare Humboldtianum, and Sinus Iridum. The Riphaen Mountains mark the rim of a small submerged sea or very large crater. All the other seas are simply overflow

areas from the Mare Imbrium region or else are local lava sheets (chap. 11).

Mare Imbrium is by far the largest of the mountain-bordered seas and shows in magnificent detail many features in well-developed form which can only be guessed at from study of the smaller seas of the same type. The great sea is tolerably circular, being roughly 700 miles in diameter and more than 340,000 square miles in area, figures which are only approximate because the exact location of the eastern border is subject to conjecture. Usually the line is drawn near Euler, Diophantus, and Delisle, but it probably should lie farther east. Almost over to the brilliant crater Aristarchus, the Harbinger Mountains timidly rise above the flood. If the curves of the Carpathian Mountains on the south and the uplands near Sinus Iridum on the north are extrapolated, they join among the Harbinger Mountains.

The long Carpathian Range north of Copernicus is but a series of peaks, crests, and ridges rising above their lava-buried bases. They are curiously worn and rounded with predominant directions of markings perpendicular to the border of the sea.

The gap between the Carpathian and Apennine Mountains offered wide sweep to the molten rock as it roared southward to form Mare Nubium. The latter range is the highest of the Mare Imbrium series and hence is best displayed. The face toward the sea is a sharp scarp, or nearly vertical wall, and in many places there can still be seen the wreckage of moon-shaking landslides where masses of rock perhaps 20–75 miles long and 10 miles broad dropped more than a mile. Many peaks on this front rise from 12,000 to 18,000 feet. The outer slope is gradual on the average and yet is almost inconceivably rough.

On the western end of the Apennines the gap into Mare Serenitatis occurs. North of this the Caucasus Mountains rise, often to great heights. In all fairness Mare Imbrium can claim only a small portion of this range, the remainder forming the eastern edge of Mare Serenitatis. The Lunar Alps are found on the northwest border of Mare Imbrium and are strangely dissimilar to the other ranges, for they are built mainly of scattered discrete peaks. From Plato to well beyond Sinus Iridum the upland border is continuous and very jagged, gradually disappearing below the level of Oceanus Procellarum on the east.

Mare Imbrium is thus an almost circular sea of frozen lava, bounded by

mountains, but having five outlets through which the lava has streamed. The bordering mountains generally rise gently as the mare is approached and then drop precipitously. Numerous faults are to be found parallel and close to the edges, while some can be detected perpendicular to the sea. The structure of the mountains gives clear evidence of others of the perpendicular fault series.

The predominant direction of the hills and valleys in all the mountains is perpendicular to the shore except near Sinus Iridum, where the markings lie radial to it rather than to Mare Imbrium.

Several hundreds of craters, mostly small, were born after the great lava flow had hardened, the largest of which is Aristillus. Archimedes is a prelava flow crater, for the flood has buried the lower parts of the outer crater wall and even obtained entry into the pit and covered its floor. Southeast of Archimedes is a portion of the original preflood floor of the region. It shows two great ridges, both parallel to the Apennine front.

An almost circular ring of scattered mountain peaks extends above the lava in the north central portion of Mare Imbrium. The ring, over 300 miles in diameter, consists of the Straight Range, the Teneriffe Mountains, Pico, and two groups of mountains north and east of Archimedes. Between Timocharis and Lambert is an isolated peak; beyond Lambert lies Lahire. Just east of Caroline Herschel is another solitary mass. The list of these mountains is not impressive; but, except for the Archimedes region, Piton, and scattered peaks near Euler, they constitute the entire group of such objects on Mare Imbrium. In addition, the ring they define is nearly concentric with Mare Imbrium and would appear even more so if it were not for the deformation of the circular border of the sea caused by the promontories of Sinus Iridum ending in Cape Heraclides and Cape Laplace. It is possible that the mountainous masses just named as not included in the inner ring may form parts of another and less well-defined ring between the first and the border of the mare.

One other type of feature of the Imbrium plain is worthy of mention, namely, the great irregular low ridges in the lava. Many of these wrinkles are known, appearing best under a low sun; but one series, in particular, is important, for it follows the outline of the inner ring of mountains completely. Quite certainly, under the lava, is the raised rim of a vast crater which is nearly concentric with Mare Imbrium.

On the west lies Mare Serenitatis, on the east is Oceanus Procellarum,

while on the southeast is Mare Nubium, all formed by or covered with lava flows connecting with the Imbrium region. North of Mare Imbrium, beyond the mountains, lies a different kind of sea, Mare Frigoris, and its extension, Sinus Roris, narrow and irregular, but running parallel to the edge of the circular mare. Beyond the Apennines is the curved band of lava containing Mare Vaporum, Sinus Medii, and Sinus Aestuum, which actually are all parts of the same structure. On both north and south, then, Mare Imbrium is bordered by raised mountains which slope outward into depressed lava-filled zones whose inner and outer edges are again concentric with the great sea. Foreshortening causes Mare Frigoris to appear narrow. Actually, it is quite similar to its southern counterpart. It is only surmise, of course, but it appears quite probable that, were it not for the obstructing factors—Mare Serenitatis, Mare Nubium, and Oceanus Procellarum—we should find a depressed zone completely surrounding Mare Imbrium and its bounding uplands.

The most amazing and probably the most important of the surface features associated with Mare Imbrium are found scattered from the mountain border of the sea to more than 800 miles distant. They are great valleys, usually a few miles wide and up to 50, occasionally more, miles long, scooped from the rock of formations older than Mare Imbrium. These valleys, and there are hundreds of them, are all lined up radially to an area in the north central portion of the lava flow covering the floor of Mare Imbrium. When the major axes of these valleys are projected backward along great circle arcs, it is found that they intersect in an area which, apparently, is outlined by the inner ring of mountains still projecting above the surface.

Thus we have, on a tremendously exaggerated scale, an enlarged version of the radial markings so often found around normal craters.

There are three main zones of these valleys, whose prime grouping is found due south of Mare Imbrium in the region of Hipparchus, Albategnius, Alphonsus, and Ptolemaeus. At this distance from the radiant the valleys are nearly parallel. They appear almost anywhere but show a preference for the higher altitudes; the rims of many craters near by are nicked and scored. The lava which has filled Hipparchus and Albategnius came after the narrow valleys were formed, for traces of submerged markings of this kind can still be seen in both pits. Similar buried valleys may be noted in Fra Mauro and other craters in the shallower portions of Mare Nubium.

Steavenson (21) attributed those furrows near Ptolemaeus to the almost tangential impacts of large meteorites.

West and north of the main group of radial valleys the direction of alignment gradually changes. In Mare Vaporum are numerous examples. These valleys are closer to Mare Imbrium and are wider than the others. Many are partially drowned in the dark lavas of the Mare Vaporum region. The near-by Haemus Mountains, which form the south border of Mare Serenitatis, have assumed an appearance much like a curved ridge of sand upon which has been turned a stream of water. The entire range has been smashed and reoriented so that its ridges and valleys point toward Mare Imbrium. Tomkins (22) noted these elongated grooves in Mare Vaporum and the furrows near Ptolemaeus but attributed them to faulting and pressure.

Some valleys of this system are also found beyond Mare Frigoris, but foreshortening here prevents their accurate delineation. The great Alpine valley and others in the Alps and Caucasus regions are also of similar origin. The former is 83 miles long, 3½–6 miles broad, and up to 10,000 feet deep.

This great fan of valleys was created before the lava floods, for none is found in the Mare Serenitatis, which is covered by Imbrian lavas, and relatively few can be seen, partially covered, in the shallowest sections of Mare Nubium.

Viewed as an entity, the Mare Imbrium system has several points of similarity to a monstrous crater and several wide divergences. No mode of origin can be considered satisfactory if it is inconsistent with any of these observed facts.

Mare Imbrium shows all these features more clearly than any of the other seas, but, strange as it seems, Mare Nectaris is its closest parallel. Mare Nectaris itself is only a small lava sea about 170 miles in diameter. It connects with Mare Tranquillitatis through a broad channel passing either side of the postflow crater Mädler. In other places the borders of the sea are fairly well defined. On the west lie the Pyrenees, which partake more of the nature of an upland plateau than of a mountain range. The average heights are about 6,000 feet. The lava-covered section is marked by several concentric low ridges which indicate a sinking of the once level surface.

Beyond the shores are other structures quite certainly associated with

the central mare. From Colombo to Santbech is a great curved ridge paralleling the lava edge. Another is diametrically opposite, joining Cyrillus and Catherina. Suggestions of still more of these structures may be found, but beyond all of them, and still concentric with Mare Nectaris, are the great Altai Mountains. Normally it is said that they start at the east wall of Piccolomini and curve northeast to near the small crater, Tacitus. Examination of photographs makes it clear that only the highest portion of the real mountain range is thus described. It averages 4,000–6,000 feet while occasional peaks may rise 11,000–13,000 feet. West of Piccolomini the curve is resumed, passing Neander, north of Reichenbach, then curving northward to Borda, disappearing near Cook, but rising briefly between Maclure and Goclenius. Thence to Lubbock the range dips down beneath Mare Foecunditatis, and only a few high peaks are revealed. From Lubbock to Censorinus it is clearly marked. Then comes the broad lava connection to Mare Nectaris after which, near Hypatia, the mountains reappear, curving smoothly toward Tacitus.

A complete and nearly circular ring of mountains, 560 miles in diameter, thus surrounds Mare Nectaris and is everywhere parallel to its shore line. The situation is exactly analogous to that which obtains at Mare Imbrium. The fundamental difference is that the lava here has not completely covered the floor. The inner mare limit may perhaps correspond to the inner ring of mountain peaks rising above the Imbrian flood. The raised ridges paralleling the shore find counterparts near Archimedes. The inner face of the Altai Mountains is a scarp only less grand than that bordering Mare Imbrium. In both cases an appreciable duration of time elapsed between the sinking of the great block and the lava flow. Fracastorius was a later occurrence than the primal cavity of Mare Nectaris as is shown by its superposition, and yet the crater is filled with the once molten rock and its seaward edge slopes downward so that the northern rim has vanished.

Just to make the similarity to Mare Imbrium even more amazing, the regions beyond the Altai Mountains, particularly in the west and south directions, are deeply furrowed. These great grooves or valleys are this time radial to Mare Nectaris. They are not as frequent as the Imbrian valleys, but about a dozen are easily recognized, averaging broader and longer but not deeper than their more numerous relatives. The greatest of these radial troughs is the almost unbelievable Rheita Valley. Starting with a gradual dip near Rheita, which is a later formation, the valley runs

for 187 miles. Its width varies from 10 to 25 miles, and the maximum depth, according to Beer and Mädler (19), is 11,000 feet; the average depth is not over 5,000 feet. A small crater apparently was formed in the valley near its center and from its position was correspondingly deformed. Another shallower valley of equal length ends near Metius, while several are found east and north of Janssen.

The longest of these strange valleys extends 500 miles. Commencing near the south border of Borda, it moves west-southwest across Snellius, going south of Haze and Adams. It is about 10 miles wide, never very deep, and can be traced only on the high spots. Apparently, whatever caused the valley acted only to disturb the crests, rims, and ridges and skipped the lowlands entirely.

Except for the concentric outer depressed zone, which cannot be detected, the phenomena of the Imbrian structure are reproduced with only minor variations in the Nectarian system. The origins of the two great features were of similar magnitude and undoubtedly of similar character.

In the same area are a few of the elongated valleys which do not belong to the Mare Nectaris group. The most prominent is about 70 miles long and nearly joins the west end of the Rheita Valley. Several smaller grooves run nearly parallel to it in the 100 miles south toward Steinheil. Along the west side of Frauenhofer is a valley about 7 miles wide; it is traceable through Furnerius for 212 miles and is of very irregular depth.

Do these few valleys, which seem to radiate from a point beyond the limb south of Mare Australe, indicate another great mountain-bordered mare forever hidden from earthbound eyes?

Mare Crisium is a dark, oval, deeply depressed sea. It is 281 miles north to south and 355 miles east to west. Foreshortening causes it to appear elongated in the opposite direction. The lava floor lies, on the average, about 8,000 feet below the rim and is somewhat concave relative to the moon's curved surface. This indicates that there was a postsolidification surface adjustment.

The interpretation of the complete series of associated structures is difficult. The resemblance of the sea and its mountainous border to Mare Imbrium is striking; yet, if this comparison is made, it must be admitted that there is a surrounding low zone, particularly visible in the north, which is even more pronounced than is the corresponding low and lava-filled zone around Mare Imbrium. The depressed ring around Mare Crisi-

um is only partially filled with lava. Its outer edge is marked by a rather sharp 2,000-foot rise running near Hahn, Berosus, Bernouilli, Geminus, Newcomb, and ending east of Macrobius. It is not prominent on other sides of the mare.

The alternate solution is to regard Mare Crisium as similar to Mare Nectaris. This would make the outer rise comparable to the Altai Mountains. This solution may be questioned on the grounds that the Mare Nectaris borders are not very precipitous while Mare Crisium is edged by veritable mountains.

The fundamental question involved is the identification of the real mountainous escarpment in each case. At Mare Imbrium it is the border of the lava flow. At Mare Nectaris it is the Altai ring beyond the lava. At Mare Crisium the choice must necessarily be the first suggestion—that the mountainous edge of the lava-filled pit is the true border.

Mare Crisium, therefore, is a small-scale model of Mare Imbrium. Although the extent of the lava flow is greater than at Mare Nectaris, the latter is, in its entirety, a larger structure.

Mare Crisium also shows numerous radial valleys, ridges, and grooves, but the system is not as well defined as the two larger ones. Several valleys lie between Cleomedes and Macrobius; a large furrow is just east of Webb.

Mare Humorum is another of these great circular seas. Smaller than Mare Crisium, it is only about 263 miles from north to south and 286 miles east to west. This mare is bordered by a poorly defined scarp, which, between Gassendi and Mersenius, is called the Percy Mountain Range.

Like Mare Nectaris there are several well-defined ridges on the lava which tend to parallel the shore. A sinking of the lava floor is again indicated. Wide openings on the northwest and southwest lead to Mare Nubium. It is probably because of these openings that Mare Humorum is more nearly filled with lava than others of its class.

The entire region surrounding Mare Humorum is lined with rills, many of which are of gigantic size. Most of these are parallel to the shore, but some are lined up at right angles.

The mountainous border of the sea gradually dips outward and leads into a depressed zone, equally ill defined. On the northeast its outer limit is marked by a low irregular ridge paralleling the Percy Mountains, 100 miles away. Traces of this ridge may be seen circling the eastern edge of

Mare Humorum as far as Capuanus. In the south the depressed zone is lava filled. It is here that the Ramsden clefts are located.

As at Mare Crisium, numerous valleys, grooves, and ridges are placed radially to Mare Humorum. They are not well marked, however, and the system is more easily identified from the predominant directions of the surrounding markings than from individual valleys.

Despite the irregular and somewhat blurred details of the Mare Humorum structure, it is apparent that we are dealing with another of the formations modeled on the Mare Imbrium pattern.

Mare Humboldtianum, lying on the northwest limb, is still another of the type. It is slightly smaller than Mare Humorum, 191 miles by 254 miles, but because of its unfavorable location little is known of it.

The borders are mountainous, averaging about 8,000 feet above the lava plain, and slope outward into a depressed zone reaching nearly to Endymion and Mercurius. A very few possible radial valleys have been glimpsed in the Endymion, Atlas, and Hercules region.

It would be hard to differentiate between the true nature of Clavius and of Sinus Iridum. The latter had the misfortune to be born alongside Mare Imbrium after the main structure was started and before the lavas appeared, hence it lost its south wall in the sinking and flooding process. Otherwise the two great craters appear much alike. Valleys radial to the Sinus are easily found in the uplands but not on the lava. It seems probable that Sinus Iridum and Clavius represent transition forms between true craters and true mountain-bordered maria.

Mare Serenitatis has been segregated from the others because it is one of the oldest, if not the oldest, of the great mountain-bordered seas, and it has been so badly mutilated that it cannot even be accurately delineated. The southern wall is formed by the Haemus Mountains. As already mentioned, they have been ruined by some process incident to the birth of Mare Imbrium. On the eastern edge are the Caucasus Mountains. Part of the interior is lava covered and tolerably circular. This section is what is usually meant by the name, Mare Serenitatis, but actually the mountain border continues far north of the edge of the lava flow. The Caucasus Range runs in a well-defined manner to Eudoxus. Probably the border continues as a ridge lying south of Bürg on the Lacus Mortis, thence following, or confining, the north shore of Lacus Somniorum until it reaches the Taurus Mountains near Bond. The latter range, which is more like an

irregular plateau than a mountain chain, then runs south to Mount Argaeus across the strait from Promontory Acherusia at the end of the Haemus Mountains.

If this is the correct outline, Mare Serenitatis is quite elongated, being about 430 by 550 miles. Others of the main structural details are not clear. No radial valleys have been found.

The lava flow which has covered so much of the floor is of later vintage than the grooves and valleys in the Haemus Mountains. At least one valley which starts in the uplands is partially filled by and extends below the Mare Serenitatis lavas, and no valleys are on the surface.

The lavas contained in the regularly bordered maria are apparently deeper than in regions like Oceanus Procellarum and Mare Nubium. In the seas of the latter type it is the rule rather than the exception to find ruined crater rims projecting above the surface. In the maria of the Imbrian type such craters are not seen except near the edges.

Several other lava-saturated regions are readily visible. The so-called Mare Australe is one such shallow field. Others are Mare Smythii, Mare Foecunditatis, Mare Tranquillitatis, and Mare Marginis. Near the western limb is a large area in which nearly all the larger craters have lava-filled floors. It lies almost between Mare Crisium and Mare Foecunditatis.

The major lunar surface features, in spite of their apparent diversities and variations, belong to a very few well-defined sequences. The interpretation of the present nature of the moon's structures is thus simplified greatly, for it is now clear that a small number of systematic forces was active during the moon's past history rather than a large number of random forces.

CHAPTER 3

Suggested Crater-forming Processes

THE earliest drawing of the moon, that of Galileo, shows few features which can be identified today, owing, of course, to the inadequacies of his tiny telescope. Even so, several vast, circular forms are outlined. They were soon given the name of "crater," derived from the Greek and meaning "cup," indicating that even at that early date the superficial resemblance to terrestrial volcanoes had caused observers to accept the apparent solution that the pits had originated in the same manner as the earthly fire mountains.

Aiding and abetting this assumption was one of the most beautiful optical illusions in the universe. The craters appear to be much deeper than they are.

Brilliant colors simply do not exist on the moon. Those which are found are better described as tints. Slight changes in tint and relatively small differences in contrast are about all that can be seen in the areas under a high sun. Consequently, attention is quickly drawn to the region of the terminator where the low sun of dusk or dawn casts long shadows, disproportionately long shadows, which make surface irregularities stand out in sharp relief. These black curtains are knife edged, not hazy with diffused light as they would be under our earthly blanket of air. The result is that the moon takes on an appearance of unreality, almost as though it were a plaster miniature, miraculously perfect, suspended near by. The craters seem to be many times deeper relative to their diameters than measurements actually show them to be. They do resemble great cups. That they really are extremely shallow proportionately is hard to realize. This optical illusion is difficult to reconcile with the facts; it exists, and, as a result, observers for more than three centuries have considered the lunar craters to be enlarged versions of the normal terrestrial volcanoes.

The extreme size of some of the lunar craters did bother many of the

volcanic-hypothesis enthusiasts, but this was passed off by the rationalization that, because the surface gravities of the two worlds differed by a factor of 6, the craters produced by applications of identical forces would also differ in diameters by the same ratio. A Clavius on the moon, 146 miles in diameter, would reduce to only 24 miles on the earth. This size is strictly comparable to the largest volcanic craters, and hence there appeared to be no inconsistency.

Two arguments may be raised against this assumption. According to Williams (23) the largest explosive craters on earth are about 2 miles in diameter. All larger calderas, with the possible exception of Tamboro, are formed by collapse rather than by explosion. He suggests that this implies a size limit to explosive volcanic craters. If this is correct and the 6:1 factor were to hold, the largest lunar craters of explosive volcanic nature would be about 12 miles across. It is quite evident without probing into the matter further that if the craters of the moon were formed by explosive vulcanism, they indicate an entirely different order of applied power than has been demonstrated on earth.

The forces in an explosion which act to produce a crater do two things. They break up the surface layers by a shearing process, and they cause, for very short intervals of time, accelerations of the fragmental rock which are from a few to thousands of times that of gravity. The main energies are used to brecciate the crust and to start the masses in motion. The forces necessary to do both operations on the moon are almost exactly the same as if the explosion occurred on the earth, for mass and not weight is involved. The moving body would fly much farther on the moon, with its lower gravity, greater curvature, and more rarefied atmosphere, but the pit whence it came would not be significantly larger than we would find on the earth; the debris would be somewhat more scattered.

If the larger lunar craters are calderas of collapse, the need to invoke the aid of the moon's weaker gravity does not exist; indeed, this factor could operate in reverse, for the rock layers would be relatively stronger than on earth and might tend to prevent the collapse or to restrict its extent. It may be doubted, however, that any considerable area of rock would long stand unsupported. Fractures are universal in terrestrial surface rock and hence presumably are present in the lunar rocks. The extent of such a crater would depend on the amount of material extruded or spewed forth. Since the time of Schröter, a century and a half ago, it has

been recognized that the rim materials of most of the moon's craters would just about fill up the pits. On the collapse hypothesis this condition would not obtain unless the subsidence followed the first major outburst. The original mountain before collapsing to form Crater Lake in Oregon was built up to a height of perhaps 12,000 feet over a period of perhaps sixty million years. The caving-in of a mountain after its disemboweling is well established as a normal process on earth. The usual caldera is oval with axes in the ratio of roughly 3:2. The essentially round lunar crater bears only superficial resemblance to the earthly caldera of collapse.

It is manifest, therefore, that the craters of the moon are not counterparts of terrestrial volcanoes. There is no single known example of a true volcanic cone anywhere on the moon's visible hemisphere. A few domelike objects have a resemblance to small shield volcanoes which, from their nature, are normally nonexplosive. When the lunar crater form is analyzed, it is found that the broad, gently sloping rim and vast sunken basin have no counterparts in earthly igneous structures. This can only mean that, if the craters of the moon are volcanic in origin, strange unknown processes must be postulated.

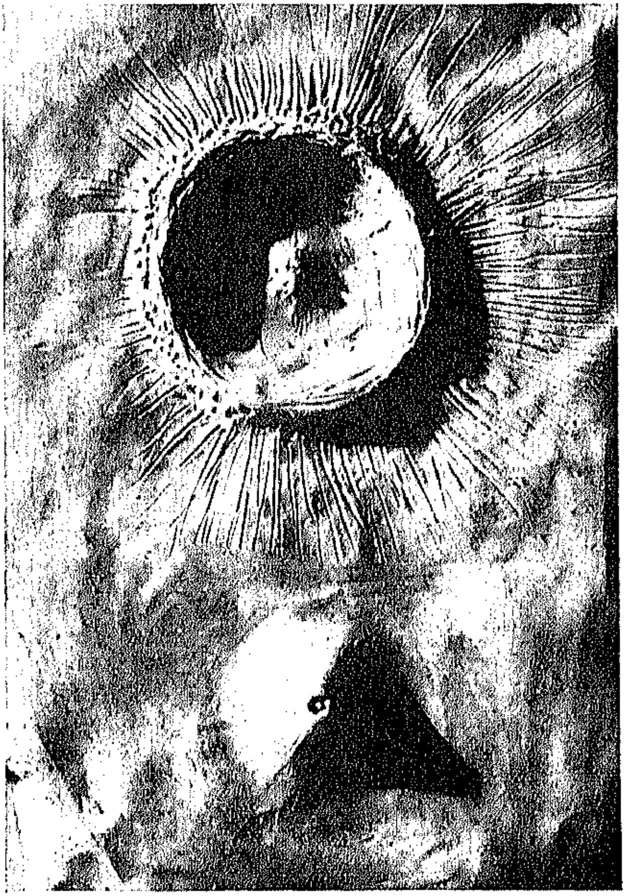
Once this point is acknowledged, the field is open. Many astronomers and others have availed themselves of the opportunity to let their imaginations run riot and have advanced and sometimes strenuously advocated other mechanisms in attempts to evolve a satisfactory lunar history. Some of these ideas border on the fantastic. Others, which are known to be incorrect, suggest authentic efforts to reach logical conclusions.

Several of these hypotheses, not in chronological order, are interesting to review.

Nasmyth and Carpenter conceived the craters to be of volcanic origin. In their book, *The Moon*, they made a serious attempt to modify known volcanic processes to fit the observed lunar conditions. They pictured a central orifice, much like that in a cinder cone or stratovolcano, spewing up finely divided and pyroclastic materials in a fountain-like manner. The debris was supposed to fall in a ring miles distant from the volcanic neck. As the explosions grew more violent, the inner edges of the ring would collapse inward, falling into the funnel, whence they would be re-ejected to greater distances than before, again building a raised ring.

Slight modifications of this basic process, it was postulated, would give the wide range of forms now seen among the lunar craters. A slackening of

PLATE VII



PHOTOGRAPH OF A SCALE MODEL OF A TYPICAL LUNAR CRATER AND A TYPICAL TERRESTRIAL VOLCANIC CONE

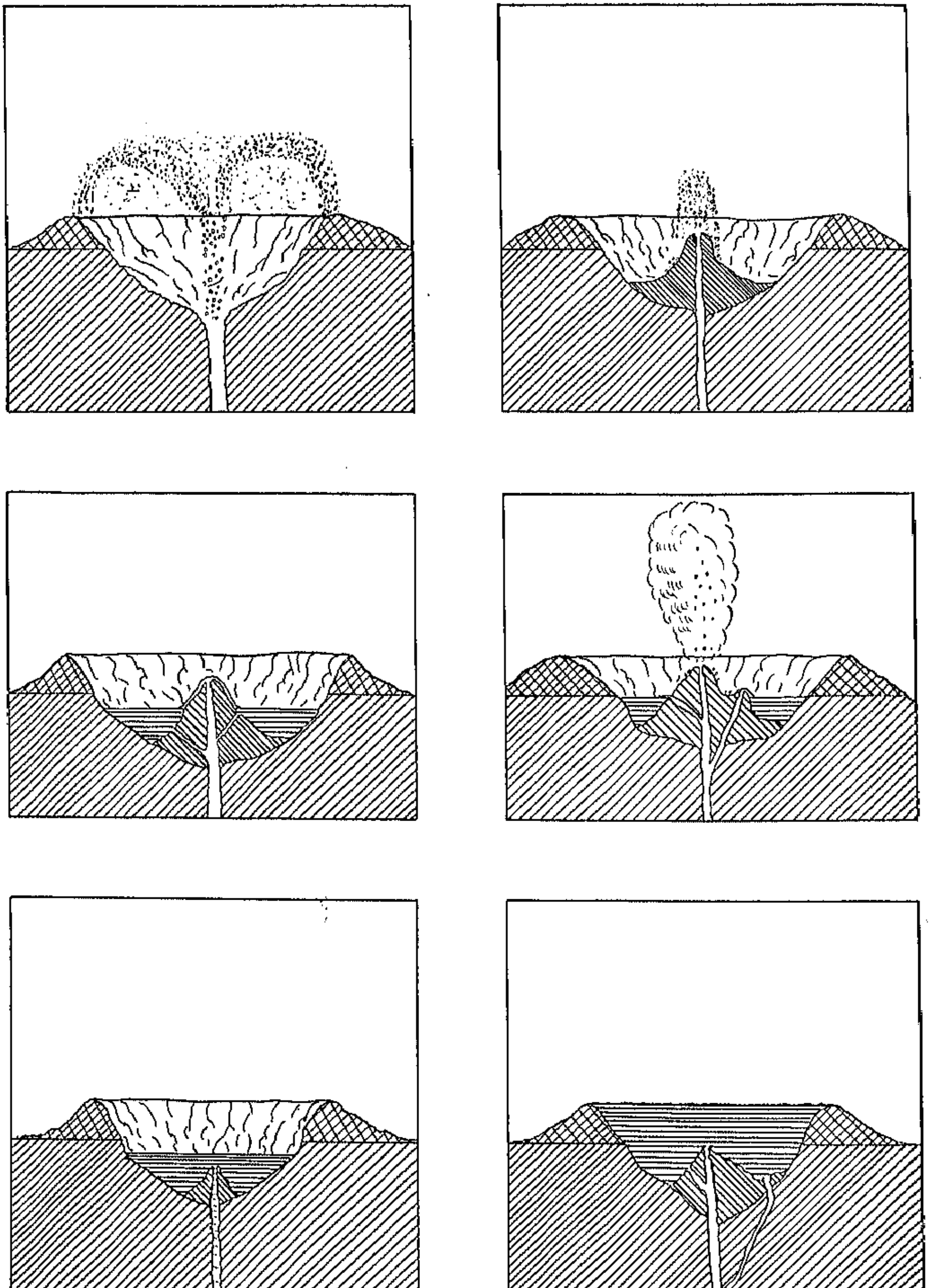


FIG. 6.—Sequence of crater forms according to Nasmyth and Carpenter

the volcano's powers might produce a central mountain peak topped by a small summit crater. As at Etna, there might develop branch openings from the main neck, and from these would grow the additional mountains of the central massif. If the character of the eruptions were to change, the fountain might be replaced by a gentle flow of highly liquid lavas which would first cover the rough crater floor and then gradually rise, hiding more and more of the central peak.

The entire sequence may be found among the lunar craters. Wargentin is filled to the brim; Albategnius shows a considerable flooding although the central peak is still prominent. The floor of Copernicus is probably raised slightly by lava; it appears to have been flattened. In Theophilus there is no trace of molten action.

Numerous arguments may be cited against this hypothesis. The angle of repose for fragmental material is never reached, even in the tiniest lunar craters, on the average inner wall slope. Since this is so, a crater could not enlarge itself by a cyclical ejection process. In this same vein the outer slope of the volcano should also approximate the angle of repose, for basically there is no difference between the proposed model and a terrestrial volcanic cone.

It is not clear how Nasmyth and Carpenter accounted for the depressed floors of the craters. It is also difficult to understand why, on the volcanic hypothesis, the central peaks never attain the level of the surrounding external plain. The drawings used to illustrate their hypothesis are faulty in this respect. So far only about 4 per cent of the central peaks in large lunar craters have been found to show summit craters although smaller ones might exist in some of the others. All would be so constructed if they were of volcanic origin.

On the outer walls and surrounding plains of many craters, particularly the newer-appearing objects, are radial ridges and valleys. Nasmyth and Carpenter felt that they were similar to the great ribs of many of the terrestrial volcanoes, especially some in the rainy climate of Java. On earth they are due primarily to erosion. On the moon it was felt that both erosion and lava flows should be called upon as partial explanations.

The generic relationship between individual craters and the great ray systems was, of course, recognized by these American astronomers, but their interpretation was that the globe of the moon had, in numerous cases, cracked divergently from a center of disruption because of internal pres-

sures and that lavas had issued simultaneously from all cracks of a system and spread thinly over the ground. The possibility of these rays being caused by "vapours which may have issued through cracks and condensed in some sublimated or pulverulent form along their courses . . ." was also considered.

S. E. Peals went to the opposite extreme. Far from claiming that the lunar craters were volcanoes, as did most early astronomers, he advanced the striking theory that the moon's surface was icebound, in fact covered much more deeply than Greenland is today. Down under the ice, however, in the rocky layers, were numerous focuses of the moon's internal heat. These heat zones melted the ice, forming pools of water. With the low air pressure existing on the moon, the liquid would quickly evaporate and then, because of the intense surrounding cold, would freeze into ice crystals and be deposited around the rim of the pool.

This guess may be disposed of very quickly. It does not account for the jaggedness of the walls of the craters, the radial marks so often found, or even the central peak. It is certain that most of the lunar craters are at least as old as the Cambrian period (chap. 10), and yet no serious amount of cold flow of the ice is found.

Nicholson and Pettit (15) have measured lunar surface temperatures and found them to be as high as the boiling-point of water (standard conditions) at the subsolar point, a condition impossible to reconcile with the existence of ice.

The atmosphere at the surface of the moon is more than one million times more rare than that at the earth's sea-level. This is almost a perfect vacuum. Even at 0° C. the vapor pressure of saturated aqueous vapor over ice is 4.580 mm. of mercury, or 1/166 atmosphere. To reach the observed maximum-density limit and still maintain an icy surface, the temperature could not rise above about −90° C.

Since there is no observable lunar atmosphere, it may confidently be stated that there is no appreciable quantity of ice on either the bright or the dark side of the moon.

One of the world's greatest observers of lunar phenomena was W. H. Pickering. His investigations were largely concerned with the detection of variations in appearance of small sections of the surface which might indicate either periodic or permanent changes in the moon's structure. As a result of his work he became profoundly dissatisfied with all existing ideas

about the origin of the craters, and so he developed a new theory of his own (24), which, however, appeared about simultaneously in England, France, and Germany. The main features were that the craters were formed in the early days while the moon still rotated on its axis relative to the earth and was closer to the earth than it is now. The primal crust was formed, when the moon began to cool, of material of lighter color and lighter specific gravity. While still thin, the crust was broached at numerous places by strains set up because of the tides caused by the earth's gravity. Every half-rotation, the tidal wave would cause lavas to rise in the opening and spill out onto the surface where solidification could produce the walls of the crater. Melting from the center would bring about the circular shape. Pickering felt that there was no evidence for the explosive character of the craters.

The larger craters would be formed during the thin-crust stage. As the shell became thicker and communication with the hot interior more difficult, the craters formed became smaller and impinged on the larger early ones.

Still later, when the shell contracted by cooling and solidification, the hot molten interior broke through the surface in much the same way as "now happens on a small scale in Kilauea, Hawaii." This was the period in which the various maria were born, nearly half the crust being destroyed and dissolved, sinking and melting from several centers.

On Pickering's hypothesis the surface of the moon evolved relatively gently in a nonexplosive manner. This is at utmost variance with the processes as they are now understood.

In modern geophysical thought there is serious question that any planet or satellite can develop a crust from the outside. The density of most crustal rocks is about 10 per cent greater than the corresponding liquids, and therefore a series of convection currents would be started and the solidification would proceed from the inside. The crust would be the last to be formed. However, the subcrustal matter, which may behave much like a solid, might easily liquefy if the pressure of higher layers were relieved.

Pickering's hypothesis may also be questioned from other points of view. The broaching of the crust by tidal action would be expected to occur along great fault lines. Consequently, the tidal craters would naturally be aligned in well-defined patterns. A few such lines of craters have been

suggested, but in most cases the group parallels the terminator and the effect is purely optical. Such alignments may be drawn in numerous other directions on lunar maps, as, indeed, they may be found in any random distribution. The distribution of lunar craters other than the few chain craters, except as modified by the superimposed lavas of the maria, is random.

If the moon once had a solid crust and a liquid interior, as Pickering proposed, then tides would lower the lava level near the poles and yield large fluctuations only close to the equator. The character of the craters should thus be a function or functions of the latitude. This is not observed to be so.

A still different mechanism, which has little to recommend it except its novelty, is one of the early ones. Robert Hooke, in *Micrographia* (*circa* 1667), suggested that tremendous bubbles, gas filled, rose slowly through the hot viscid matter of the primitive surface and then burst. Solidification occurred, leaving vast crater scars which became successively smaller as the viscosity increased. This theory was undoubtedly developed as a result of watching hot mud flats which are known in many volcanic localities. Similar bubbles are to be seen in a pan of boiling fudge. Larger ones are famous in Arizona where in some of the congealed lava vesicules several men can stand.

Intriguing as Hooke's suggestion is, it is mechanically impossible to produce such vast bubbles as are necessary, often over 100 miles across, or to account for the presence of large, perfect craters such as Pythagoras, Copernicus, and Tycho, which obviously were formed long after surrounding smaller objects. Other features such as the central peak could not be explained, and so the idea was quickly relegated to the limbo of forgotten things and has been resurrected only for historical reasons.

Another strange hypothesis has recently been revived by Davis (25); it was first mentioned by Beard (26). The gist of this proposal is that the craters on the moon were not the results of meteoritic impacts or volcanic action but were formed in a manner similar to the coral atolls in our oceans. The coral island reefs are records of organic growth, and it is claimed that what we see on the moon are limestone formations and that the moon's surface really is the bed of ancient seas in which coral atolls were formed by lime accretions.

Pickering killed the idea of the past existence of large bodies of water on the moon when he said, "The lunar atmosphere, on account of the gravita-

tive constant, can never have been very dense, like our own, and the rapid evaporation from extensive lunar oceans under low pressure and exposed to the tropical rays of the sun would have produced deeply eroded valleys and extensive river systems, which are conspicuous on the moon only by their absence" (24).

J. E. Spurr (27) has proposed a model which is a composite of Hooke's hypothesis and a form of vulcanism. He has divided the craters into three main groups: cirques,[1] caldera craters, and blowhole craters, with transition examples between. His study comprised only the Mare Imbrium region:

> Blowhole-craters . . . are among the most remarkable features of the moon's surface; they are numerous although they are not conspicuous in size. . . . They are circular openings, quite smooth and regular, surrounded by a low and even wall. So smooth and even are the surrounding wall-ridges, and so smooth the curved walls of the pipe-like or funnel-like interior, that the illuminated area caused by the sloping sun shining into the interior is almost a perfect crescent. . . . In some cases a blowhole-crater is surrounded by a small system of rays, commensurate with the small size of the crater; exceptionally, therefore, the outbreak was explosive. . . .
>
> The blowhole-craters are in some localities aligned, as if they arose along a line of weakness.
>
> To terrestrial eyes these "small" blowhole-craters would not be unimpressive: the largest of those scattered on the Imbrian plain are around 5 miles in diameter, and so down to smaller dimensions. The size of the orifice is large out of all proportion to the outer wall ridge. The geometrically circular outlines preclude the supposition of the origin of the pipe by sinking; and there is no step-faulting around the inner margin, as is the case with the caldera-craters. It is difficult to account for their origin except as "blowholes" in the lava of the Imbrian plain, and that they were formed by rising gaseous concentrations, at a certain critical period of the cooling, when the lava was still viscous—yielding enough to be pressed aside without shattering, firm enough so that the cylindrical or funnel shaped aperture of eruption was not closed by the inflowing of the walls. The rims are such as well might be accounted for by the pressing apart of plastic walls, bulging out on the surface. . . .
>
> It is seen that where the crust was tougher a moderate gush of gas would not overcome its resistance; a succession or accumulation of gushes would be necessary before the surface could be broken. Thus, beneath the crust a lens, column, cushion, or mushroom of volatile material would be banked up; and the final upheaval would be over wider areas, producing caldera-craters or cirques.
>
> In the case of those, usually larger depressions which have been formed by the pressure up, down, and laterally of gas accumulations under a restraining film, the ultimate form probably has depended both on the toughness and thickness of the film, and on the degree of fluidity of the substratum. Where the latter was very fluid, the cavity at the end was shallow and flat-bottomed, resulting from the immediate rising

1. The term "cirque," as here used, does not have a glacial connotation as it often does on the earth.

up of the floor after the escape of the gas lens; where it was more viscous, deeper calderas or cirques resulted. In the case of large depressions, the original gas-filled cavity was probably always fairly thick as well as wide; the rising of the bottom, after the deflation, determined the shallower or greater depth, and also the low or high marginal walls.

The conclusion is that in some of the smaller dish- and caldera-craters, at least, the present opening was entirely the result of the initial inflation and subsidence. . . .

Spurr explains the substantial collar of coarse ejectamenta on the steeper slopes of the outer walls of numerous craters as "probably the consequences of the bursting of the center of the inflation to form the crater."

Certain objects, such as the strings of craterlets along faults west of Copernicus and elsewhere, are definitely igneous in origin. The great majority of craters are not. The same objections pertain to Spurr's hypothesis as to that of Hooke. The strength-of-materials argument alone is sufficient to cause the proposal to be rejected; but, when it is realized that all forms of craters are to be found in other sections of the moon's surface which obviously could not have been in a "plastic" condition at the same time as Mare Imbrium, the argument breaks down entirely. Tycho in the bright uplands is certainly similar to Aristillus on the Imbrian lavas, and yet Tycho is certainly postmare and post-"plastic" stage.

H. G. Tomkins (28) has advanced another rather strange theory to account for the lunar craters. It has recently received some backing from Marshall (29). In its main features it postulates a solid crust under which is formed a laccolith. Although they are not as well known as many other geological formations, there does not seem to be any serious question among most geologists that there actually are numerous laccoliths on the earth, but they can be found only by geological prospecting, for they were formed slowly and erosion almost kept up with their growth.

A laccolith is typically a lens-shaped mass of igneous rock intrusive into layered rock. It has a flat floor and is more or less circular in ground plan [30].

Instead of spreading widely as a relatively thin sheet, an injected magma, especially if it is very viscous, may find it easier to arch up the overlying strata into a dome-like shape [31].

Marshall (29) has quoted Tomkins:

Consider what might have happened in the case of a laccolith which, originating on the Moon in a way similar to those on the Earth, instead of solidifying, continued (as some of those on the Earth doubtless did [—R. K. M.]) to force up more and more molten magma, and further and further to uplift the lunar crust. The result would be that the crown of the dome would not eventually burst like a bubble, but fissure comparatively quietly, owing to pressure from below, thus allowing the top of the dome

to fall piecemeal into the lava within, where it would probably melt or eventually be deposited on the floor. Until pressure was relieved, the dome itself from the base would continue to rise, and also, of course, to extend, and the lava with it, cracking and melting the edges at the top, and forming a lava lake which, as time went on, would grow larger and larger and bring down the overhanging walls, until they had practically all fallen in. At length a stage would be reached at which equilibrium would be established, and after that, as we see in the Hawaiian craters and others still on the Earth, only on a larger scale corresponding to the greater action at the time, the lava lake would subside, and in the end would leave a floor depending for its size on the extent of the upheaval, and for its form on the extent of the retirement of the molten magma, either above, equal to, or below the original level of the crust according to the extent of the evacuation. . . . The formation would be hollow, and the result ring-shaped in form and not a solid cone. . . . Central peaks, smaller craters or craterlets . . . would follow from the nature of the laccolith from which the formations themselves arose. . . . A central peak would no doubt arise from the central pipe in case of a subsequent minor eruption if the pipe were still open or not firmly closed by cooling. If there were more pipes than one, more peaks would be caused in the same way.

[Marshall continues:] To clinch this argument we find laccoliths on the Moon. There are two near Arago, two others near Linné, many in the neighborhood of Hortensius and Milichius (east of Copernicus), some in and near Darwin, and one east of Kies. Some are low and barely discoverable; others are high. Some are smoothly rounded, others have the beginnings of crater pits in their summits. Careful study will probably show a complete sequence of these formations, ranging from the lowest of elevations to craters half formed.

The existence of a small number of low domes on the moon is unquestioned. The positive identification of these domes as having been caused by laccoliths is scarcely on as firm a foundation. However, even if they are laccolithic, can they be identified as incipient craters which somehow failed to complete the proposed cycle?

The laccolith on the earth was formed from magma at a temperature only slightly above the freezing-point. In only one known example was the surface crust broached by the updoming and postulated melting process. This object lies east of Flagstaff, Arizona. It consists of a dome of igneous rock with a mantle of upturned sedimentary rocks on its flanks. No crater was formed in the fracturing of the crust, and there was little, if any, melting of the sedimentary rock by the heat of the igneous materials. It bears little resemblance to any structure on the moon.

The supposed lunar laccolithic process represents an extrapolation from the known forms into the region of the unknown. The Hawaiian volcanoes are not of laccolithic character.

The form of the typical large lunar crater (not the so-called "walled plain") is best shown in the beautiful cross-section of Theophilus (Fig. 7)

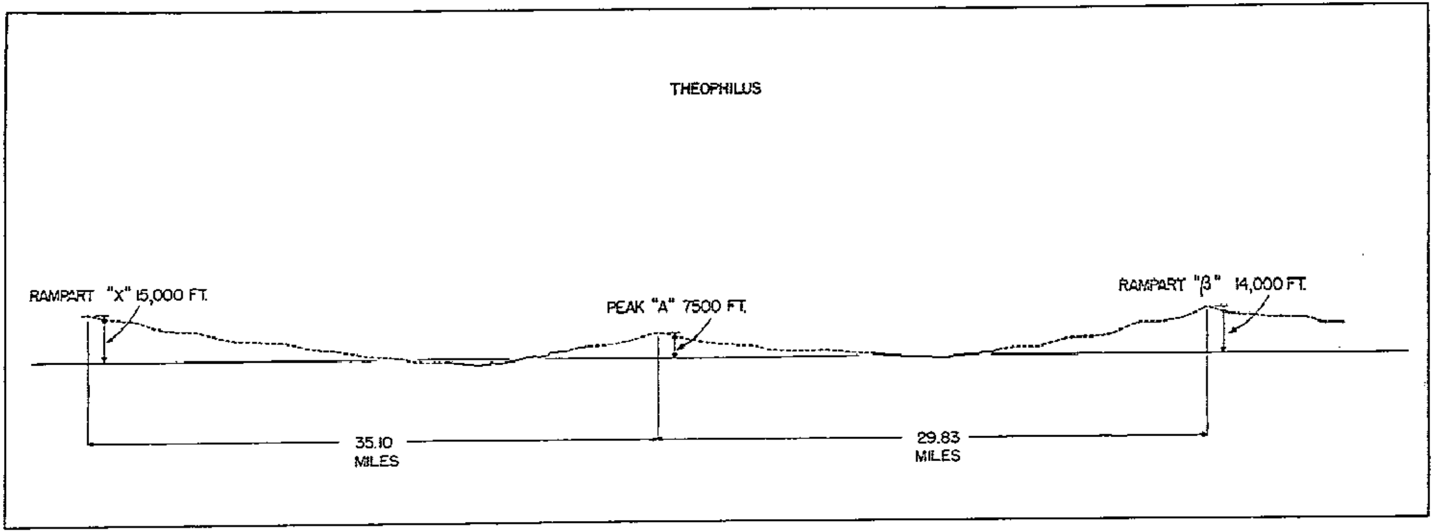


FIG. 7.—Measured section across Theophilus. (Redrawn from *Pub. Obs. Mich.*, **6**, No. 8, 67, with vertical and horizontal scales equal)

derived at the McMath-Hulbert Observatory from their motion pictures (32). In no place is the floor flat. This is difficult to reconcile with the suggested lava-pool hypothesis.

The rim craters, such as Thebit A on the northeast wall of Thebit, cannot have been caused by a laccolithic updoming. The magma would have broken through into the main crater before the dome could have properly developed.

The lunar craters are usually surrounded by a zone of jumbled breccia, much like that of the Arizona Meteoritic Crater, and often by radial markings such as could have been caused only by violent explosive action. These are inexplicable on the Tomkins hypothesis.

Schröter's Rule, that the rim materials of the lunar craters would just fill the pit, is easily understood if the explosive nature of the craters is assumed. It is not consistent with any nonexplosive mode of origin. The rays, which are so conspicuous at many craters, find no explanation on a quiescent, fracturing, and melting model.

Since the laccolith, to be effective, must raise a dome high above the crust, the pressures on the magma must be enormous, and, hence, if a stable lava level were ever reached, it would be above the lunar surface. It is strange that the pressures lasted just long enough to produce the craters and then were relaxed to allow the juices to withdraw below the ground. Over 99 per cent of the crater bottoms are sunken, often thousands of feet. The Wargentin-like craters are extremely rare, and, while they certainly froze while filled with lava, the liquids did not necessarily arise from laccoliths.

All the lunar domes so far identified are found on the great lava flows. None has been seen in the bright uplands. This seems to imply a generic relationship which is at variance with the fact that the bright regions are densely crowded with craters.

With so many physical facts opposed to a highly speculative hypothesis, there is only one choice to make. The lunar craters were not formed by laccolithic intrusions and updomings or by any other nonexplosive method. The evidence is conclusive in this respect.

Numerous theories of the origin of the moon's craters have been proposed and found wanting. Many variations of these have also been suggested. The earliest mechanisms were advanced as far back as the first telescope. A few are recent. The modern theory that craters could be

formed by meteoritic impact is relatively new. The basic idea was first formulated by the German astronomer Gruithuisen, but the credit is generally given in the literature to Proctor (33). Newcomb (34) referred to it as an astronomical curiosity.

Although the impact theory was proposed during the last century, it was not stated in the present form and many scientists refused to accept it. The original idea was that vast meteorites struck the moon with terrific violence. The mechanical force of impact gouged out craters by a splashing process in a semiplastic lunar crust. Much local melting was supposed to have occurred. It was not realized that the high velocities of meteorites implied extreme kinetic energies and that, upon the sudden stopping, these energies must have been released so rapidly that the portions of the meteorite and ground which were in contact were vaporized; the main mass of the meteorite was relatively unaffected by the generated heat and little liquefication occurred. The resultant explosions were capable of blowing gigantic craters in the rocky lunar crust even though the meteorites were tiny relative to the size of the craters. It is entirely unnecessary to call upon a plastic crust.

Experiments conducted by the United States Army Ordnance Department during the recent war have shown that inert missiles will explode on striking a solid at 4–5 miles per second.

Shaler (35) attributed the maria to impacts from bodies 5–10 miles in diameter but, like Humphreys, preferred a model based on nonexplosive ebullition of lava to account for the craters and mountain ranges. The latter were formed, they thought, from very viscid lavas; the Altai Mountains were born in this manner and by accompanying faulting.

Nölke (122) has concisely summarized several theories of the origin of the lunar surface features in his treatise on our planetary system. He leans in the direction of a meteoritic impact mechanism but specifically limits the meteorites to fragments formed as by-products of the separation of earth and moon. The craters, on his hypothesis, developed from the low-velocity impacts of these small bodies and the moon very early in the latter's history while the earth and moon still possessed a common atmosphere.

As the recession of the moon proceeded, the height of the tidal bulge decreased. Hence, Nölke feels that the moon's surface area became smaller and then great faults developed, releasing the inner magmas to form the

maria. Over- and underthrusting accounted for the mountains of the type of the Apennines. The lava flows themselves are now depressed because they have overlain the broken crustal areas.

There is no reason to believe or to disbelieve that the lunar craters were formed by low-velocity impacts. Either high or low speeds could have produced the observed explosion pits. The higher the velocity, the smaller the meteorite necessary. However, it is not now believed that the earth and moon were ever combined into one mass. Jeffreys (10) demonstrated this after Nölke's volume was published. Until further evidence is found, it must be assumed that high-velocity meteorites were somewhat more probable than the slower objects as the source of the moon's craters.

Nölke suggests that the central mountain peaks of the craters are the remnants of the original meteoritic bodies, but inspection of the profile of Theophilus (Fig. 7) shows clearly that the mountainous mass there is too large to be the meteorite, for at any possible striking speed the available energy would have been far too high to have yielded as small a crater as Theophilus.

It is less easy to follow Nölke's reasoning with respect to the maria. As the moon departed and the tidal bulge faded, the area of the moon would, of course, decrease with accompanying compression, unless the cooling of the moon's interior caused a compensating reduction of volume. On the earth the reduction in volume of the core has led to the formation of long linear ranges of folded mountains. On the moon all mountain ranges are portions of nearly complete circles. It would appear that the basic mountain-building forces were different in the two examples. If one is a surface compression, the other probably is not of that type. It is easy to account for linear foldings by appeal to tangential forces. It is not clear how these forces could lead to circular structures. The mountain-bordered maria are never symmetrically placed with respect to the tidal bulge.

The great and versatile G. K. Gilbert (36) in his address as retiring president of the Philosophical Society of Washington in 1892 came the closest of all to formulating the main process by which the major lunar surface features are believed to have been chiseled.[2] He identified the craters

2. Gilbert's address was brought to the writer's attention by R. A. Daly, professor emeritus of geology, Harvard College, during an exchange of letters discussing two short papers which the author had published covering the interpretation of the markings radial to Mare Imbrium and other maria. This is a beautiful example of the old truth that information, once lost or hidden, will again be discovered independently.

as having been produced by meteoritic impact, after having eliminated as impossible other proposals previously advanced to account for these structures. However, he made the error, common at that time, of assuming that the pits were formed by mechanical impacts rather than by tremendous explosions. The relative lack of oval craters led to an arbitrary assumption, which cannot be justified, as to the paths the meteorites could follow.

Gilbert's greatest contribution was the realization that the peculiar orientation of certain grooved markings relative to Mare Imbrium made it clear that an explosion vast beyond comprehension had occurred near the center of this sea and had hurled much material at high speeds radially in all directions. He attributed this explosion to the impact of a great mass and called Mare Imbrium the moon's biggest crater, instead of a structure larger than, associated with, and subsequent to the original crater (chap. 11). Strange as it seems, Gilbert did not realize that several others of the maria are smaller editions of Mare Imbrium and have similar associated features. Unfortunately, Gilbert's great ideas were never generally known to astronomers, and hence selenology did not take the big step forward it might have made fifty years ago.

It can easily be shown that upon any reasonable hypothesis the meteorites must strike the lunar surface at all angles from horizontally to vertically with small angles being more common than large. The absence of large numbers of elongated craters was a stumbling block in the way of early acceptance of the meteoritic impact theory, but when it was realized, first by Gifford (37), that the crater was not caused by the original blow but rather by the violent, explosive struggle of suddenly generated gases to escape, the regularity of the crater forms could be explained and the theory of the suggested process adopted.

It should be pointed out that for the first two centuries after Galileo the existence of meteorites themselves was questioned. It was not until great amounts of evidence were collected that it was agreed that bodies could fall from heaven.

Pickering has objected to the meteoritic origin of the lunar craters on the ground that accretion of meteoritic masses in space would cause their average size to increase, and hence the most modern craters would be the largest ones. The latter is not observed to be the case.

It can be answered that the observed meteorites which are now striking the earth are still so small, usually, that it is evident that accretion has

not been a very powerful factor in sweeping the solar system clear of tiny masses.

It has also been stated as a criticism that there are far too many examples of small craters formed on large craters and too few large craters overlapping the smaller pits. Two points must be considered here. There are only about 150 craters larger than 50 miles in diameter; there are perhaps 200,000 visible craters smaller than this limit. On a distribution random in both space and time, we should not expect many large craters to be superimposed on others of similar size, but we should expect exactly as many small craters under the large ones as above. However, if the large crater were formed after the small one, it would obliterate the latter. Only if a fairly large proportion of the small crater projects beyond the rim materials of the larger crater will the overlap be recognized. These statistical conditions are realized on the moon. In any given region there is approximately a random spatial and a random temporal distribution of normal craters.

Most of the arguments against the meteoritic origin of lunar craters have been raised largely because of incomplete knowledge of the nature of the physical processes which occur when a large, rapidly moving body strikes a solid surface. It is true that many details are still unknown or have been but imperfectly glimpsed, but sufficient data have been gathered and will be reported in subsequent chapters to show that there is no single observed fact which runs counter to the impact theory and that there is a whole host of observations which point unambiguously in that direction. This is not the case with any other hypothesis so far advanced to explain the lunar craters.

It can be stated, consequently, that all observations point to the conclusion that the great majority of the lunar craters were born in gigantic explosions, that these explosions were caused by the impact and sudden halting of great meteorites, and that the main features of the moon's crust were established in the first quarter of its life as a satellite.

These points will be demonstrated.

CHAPTER 4

Terrestrial Meteorite Craters

AN ASTRONOMER on a lonely vigil in the night with his eye glued to the telescope notices an almost instantaneous flash, a streak of pale light crossing his field of view. Two lovers, strolling arm in arm, find romance in a shooting star which flares and dies in a brilliant sky. Idly each makes a wish as millions have done for ages past. An entire section of a countryside comes rigidly to a pause, all eyes upraised, as a mighty pencil of flame hurtles in a vast arc, lighting the world below.

These are familiar occurrences. Everyone knows the shooting star, or meteor. Even the very bright ones are accorded only a line or two in the newspapers. Yet how many stop to think that each meteor records the death of a tiny world, a body as old or older than our own earth?

Under average conditions on clear, moonless nights an observer will note about ten meteors per hour (13). As only a very small portion of the earth's atmosphere can be seen from any one place, it can be calculated that this small number actually represents per day over the entire earth a total of more than seventy million meteors bright enough to be seen by the naked eye. The total daily mass of meteoritic material striking the earth's atmosphere has been estimated to be approximately one ton. Half of this comes from meteorites which crash through the air and land on the surface. The rest gradually drifts down in finely divided form—the residue from tiny burned-out meteorites. Over the last 2,000,000,000 years accretion at this rate would have yielded a layer over all the earth approximately 1 cm. thick.

It is clear that existing data indicate a rapid decrease in the numbers of meteorites as their masses increase, but it would be unwise to attempt an extrapolation which might tell how many meteorites of extreme mass would strike the earth in any given time interval. The necessary facts simply are not known. Numerous small meteoritic masses reach the

ground daily, but these merely represent the remains of larger bodies which have been so slowed up by the resistance of the air that they have reached terminal velocity.[1] They do not possess high velocity or high kinetic energy. The frequency of collisions between the earth and meteorites massive enough to penetrate the atmosphere and strike the surface with a high velocity is exceedingly low. In all recorded history only one such impact has been observed, that in Siberia in 1908.

Nevertheless old Mother Earth shows a somewhat pock-marked face. In recent years it has become increasingly apparent that there exist numerous small craters on the surface, which, beyond the shadow of a doubt, were produced by the explosions resultant from the impacts of high-velocity meteorites.

Scientists, as a rule, are derived from a cautious strain. They demand proof of statements, hypotheses, and theories before accepting them; but, then, having established the validity of a thesis, they will use it as a foundation on which to build further progress.

So it has been in the field of meteoritic study. Even as recently as the time of Thomas Jefferson, that esteemed gentleman questioned the authenticity of certain stones reputed to have fallen from the sky. Inevitably the proofs of the interstellar and interplanetary nature of these bodies accumulated until even the general public came to accept meteors and meteorites for what they are.

When these facts became evident, attention was directed to the possible effects meteorites might have upon the earth, in particular to the search for and recognition of the regions where high-velocity meteorites had landed. Progress was slow, however, and it was not until the turn of the present century that the Barringers (38) positively identified the Coon Butte crater of Arizona as having been caused by the impact and explosion of a large nickel-iron meteorite. The principles and criteria with which the Barringers worked are still accepted as standard today. All the more familiar forms of crater genesis, volcanic action, steam blowouts, sinks, etc., must be eliminated. Meteoritic material or derivatives from it must be discovered associated with the crater. Then and only then is the structure considered as being of proved meteoritic origin.

The process by which a small meteorite forms a moderately sized crater

1. The velocity is controlled by a balance between air resistance and gravity, i.e., a free fall.

is purely one of explosion. Other processes enter into the production of the gigantic pits such as we see on the moon (chap. 10), but the known terrestrial meteoritic craters were all blasted into being by the almost instantaneous release of the kinetic energy of motion of the mass. In all but the very smallest bodies, meteorites reaching the surface of the earth will possess far more energy than an equal mass of any known chemical explosive.

Gifford (37) was probably the first to point out that such craters could be formed by explosion rather than by the simple process of splashing, attendant upon the impact of a high-velocity punch. He demonstrated the great energies developed in collisions of the moon with meteorites and the corollary that great meteoritic masses were not necessary. From these, he drew the correct inference that even oblique impacts could lead to circular craters.

Numerous studies made by the United States Army and Navy show conclusively that shells and bombs, regardless of striking velocity, are stopped in the ground within 0.1 second. The higher the velocity of impact, the greater is the rate of deceleration and the more rapid is the rate of release of energy of motion. Even the high-velocity meteoritic masses moving more rapidly than the velocity of shock waves in the earth's crust must be brought to rest within a small fraction of a second.

Hence the three conditions necessary to the formation of an explosion crater are fulfilled. The meteorites bring with them large quantities of energy and the energy is released rapidly, close to the surface.

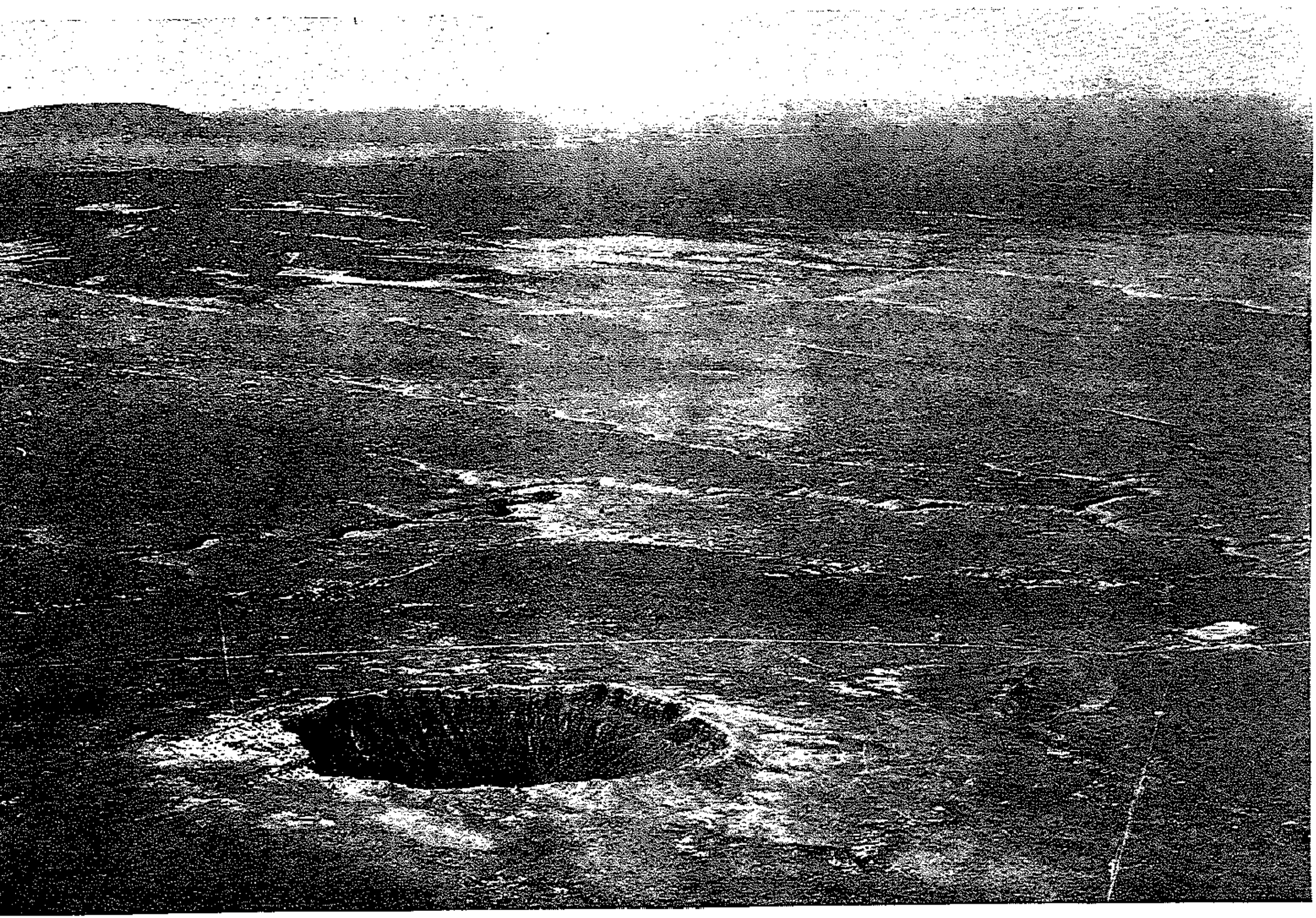
In the following pages are brief descriptions of the relatively numerous small craters which are known to be meteoritic.

AMERICAN CRATERS

THE GREAT ARIZONA CRATER

Between Flagstaff and Winslow in a level plateau of sedimentary rocks lies the greatest authenticated meteoritic crater of the world. It was brought to attention in 1891 by the discovery of meteoritic iron near by. For many years previously it had been called Coon Butte, for its upraised rim, as seen from a distance, resembled, somewhat, one of the flat-topped buttes which are frequent in those regions.

Although the nearest extinct volcanoes are only 30 miles away in the San Francisco Mountains and there are old lava flows within 10 miles, it was quickly realized that the structure was not volcanic in origin although it was once suggested that a steam explosion formed the pit.



Aerial View of the Arizona Meteorite Crater (Official Photograph U.S. Air Forces)

At present the crater is about 4,150 feet in diameter and is roughly circular. Exact mapping of the region has brought out the interesting point that the rim, which rises from 120 to 165 feet above the surrounding plain, is not perfectly round but tends to be polygonal. The present depth is about 570 feet from the rim to the floor, which is covered with lake deposits roughly 100 feet thick, indicating an original depth of nearly 700 feet for the crater.

Drilling has shown that undisturbed sandstone lies 620 feet below the present bottom, and to reach this depth the drill must pass, first, through a thick layer of fine rock flour (pulverized sandstone) and, then, through crushed and metamorphosed sandstone. Great quantities of rock flour were created, some to remain in the pit, some to be scattered broadcast. Barringer (38) calculated that about fifty million tons of this powder were thrown out of the crater, perhaps 15–20 per cent of the total mass ejected. Occasional fused and spongy rock fragments known as silica glass are to be found, both in and around the crater, and some of these contain tiny particles of nickel iron.

Thousands of small metallic meteorites weighing from an ounce or so up to one thousand pounds have been recovered over a large area adjacent to the crater. It seems certain that the main mass was shattered in the explosion and that many of the fragments were ejected along with great numbers of rock particles and blocks as far as 6 miles from the rim. Visitors have long since removed most of the surface meteoritic material, but more is still being found by electrical and magnetic detectors, buried beneath the surface. No sizable metallic fragments have been found within the crater.

Some of the pieces which have been exposed to the elements for long periods have been converted more or less completely into shale balls—sand grains cemented together by iron oxides.

The Barringers sent numerous drill holes into the crater bottom but, having found no meteoritic material, continued the drilling in other sections of the floor and rim. Those drill holes in the southern part of the crater floor went deepest before striking the undisturbed rock layers. The peculiarities of the rock structure also suggest the southern section of the crater as the focus or center of the explosion. This implies that the meteorite came from the north at an angle of perhaps 45°.

The rim of the crater slopes gradually outward and reaches the level of

the surrounding plain in about one quarter of a mile. The rock strata (carboniferous) in the northern rim, as evidenced by the exposed sections, have been forced up and now dip outward at about 5°, but this radial dip increases in each direction until the strata stand nearly vertical in the southwest and southeast. All along the southern rim the layers have been uparched to a maximum of 100 feet. The rock layers of the crater thus exhibit a distinct bilateral symmetry as contrasted with the nearly radial symmetry of the pit.

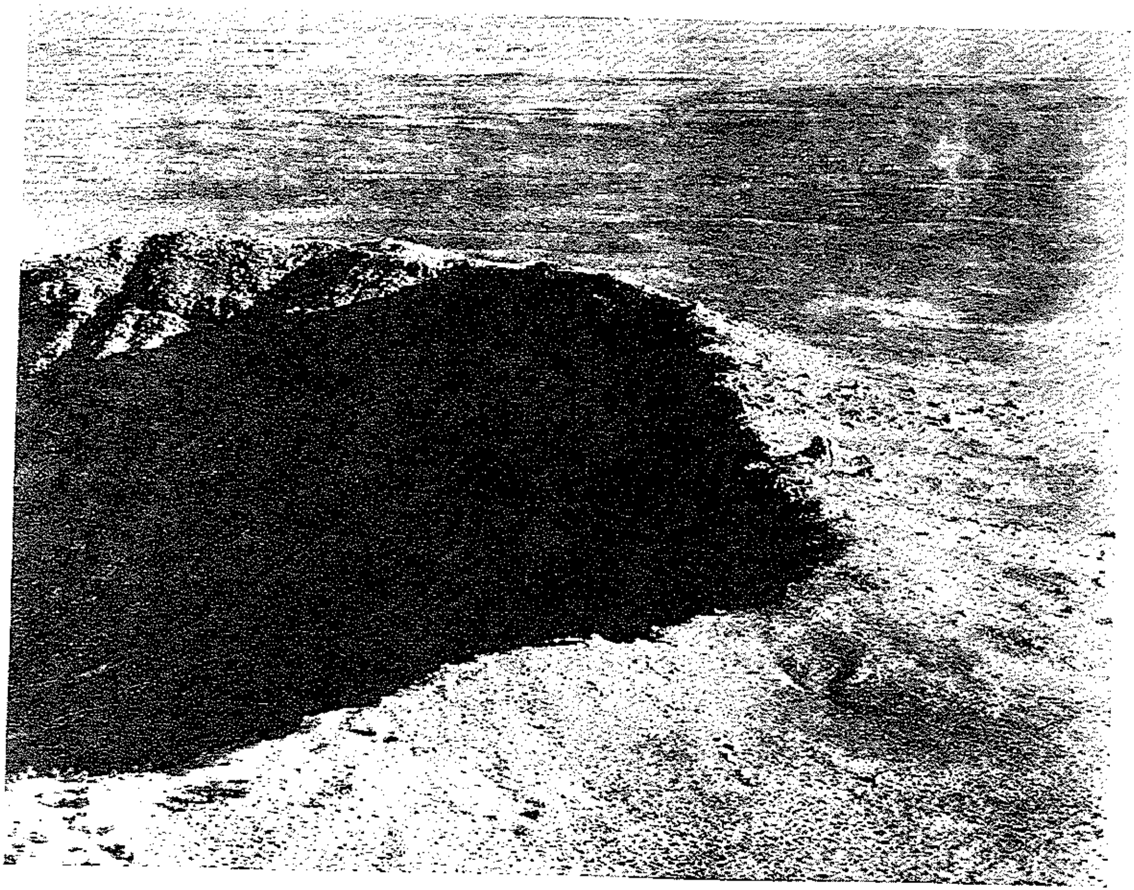
The radial uparching of the rock layers is a direct consequence of the fact that the effective upward force of the explosion is very much greater than the downward force of percussion. Hence the rocky strata around the crater walls are blown up and dip radially outward instead of toward the center as might have been expected. This uparching must be a common feature in all large explosion craters.

A drill forced through the southern rim went 1,200 feet deep before it encountered a region in which there were increasing amounts of meteoritic material. At 1,350 feet there was 75 per cent nickel iron, which made the boring exceedingly difficult. After a few feet through this region the drill stuck and could not be withdrawn. Electrical and magnetic measurements give indications that a considerable amount of meteoritic matter lies near this spot, but the exact location, quantity, and state are not known. It may be that a large portion of the meteorite was left here by the explosion of the main mass, or perhaps there is only a dense local grouping of small fragments. An attempt was then made to sink a shaft outside the crater to 1,500 feet and then to strike horizontally toward the supposed meteorite, but when a heavy flow of water was encountered at 640 feet, the project was abandoned after the expenditure of $293,000.

Fairly complete maps have been drawn of the nature of the crater itself and of the surrounding rock strata. Essentially nothing is known of the effects this impact and explosion had on the underlying layers. An exact determination of the type and degree of change which has occurred would be not only extremely interesting but of major importance to astronomers and particularly to geologists, for it would deliver into their hands a powerful tool to use on the problems concerning the past history of the earth.

Nininger (39) gives a graphic description of the fall of the meteorite as it might have been witnessed by some ancient Indians, but other authors feel that the crater cannot be as recent as Nininger would imply. The con-

PLATE IX



Rim of the Arizona Meteorite Crater (Official Photograph U.S. Air Forces)

dition of the crater and the existence of the rusty balls of iron shale indicate that it was not formed recently. It may be five thousand to fifty thousand years old, but even these estimates show that the structure is extremely young, geologically speaking. Legend has it that there is an additional smaller companion crater father north, but this has never been located, if indeed it even exists.

Early guesses as to the size of the meteorite were in the neighborhood of 500 feet. Wylie's (40) recent estimate suggests that it was of the order of 50 feet in diameter.

THE TEXAS CRATERS

In western Texas, not far from the town of Odessa, lies another great American meteoritic crater. It is smaller and far older than the one in Arizona and differs in that it is accompanied by at least two additional smaller craters. The main crater was discovered in 1921. It is in a region of horizontal, light gray limestone strata, and because of its age the crater has been eroded and filled in to the point where it is not conspicuous. According to the contour map of Monnig and Brown (41) the diameter is 550 feet with a greatest depth of 14 feet. They suggest that erosion is the cause of the present irregular form. The rim averages 7 feet high now, occasionally rising to 12 feet. It is marked by numerous rock fragments. The rock strata where they are exposed as outcrops on the inner slope dip 20° to 30° radially outward. They are buff colored, for they contain numerous minute particles of iron oxide.

Nininger has gone over the crater and surrounding area with a magnetic plow and collected 1,500 metallic fragments ranging up to eight pounds. Magnetic measurements by Sellards (42) indicated a rather large mass under the crater, 164 feet from the surface; but, when it was reached by shaft, it was found to be a very hard, firmly cemented sandstone, quartzitic in nature. Calculations suggest that a total mass of the order of one hundred tons, perhaps less, formed the main crater.

The Bureau of Economic Geology of the University of Texas has undertaken the excavation of the craters. Sellards and Evans (43) report that the crater bottom originally was 90 feet below the surrounding plain and that the base of the rock flour formed in the pit lay 13 feet farther down. It is clear that the explosion did not clean out the pit, i.e., much fragmental and pulverized material stayed in or fell back into the crater. This phe-

nomenon is well known in shell craters, on one hand, and in the Arizona crater, on the other. The rim must have risen about 40 feet.

The vertical cross-section of the Odessa crater, as given in Figure 8, shows that the tangential thrust of the explosion compressed the rock layers until they buckled, producing a ring anticline surrounding the pit, under the upraised rim. It exhibits bilateral symmetry.

Digging within the pit has brought to light an amazing fact. Normally the age of a meteoritic crater is nearly indeterminate. One can merely say that the crater was not formed within historic times and is younger than the youngest of the disturbed rock layers. In the case of the No. 1 Odessa

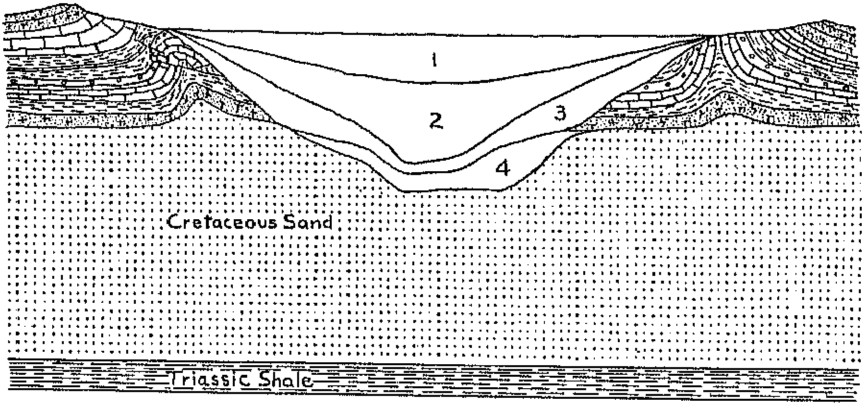


FIG. 8.—Section across Odessa meteorite crater (redrawn from 43); *1*, latest silt and sand; *2*, older silt, sand, caliche, and pebbles; *3*, fragmental rock; *4*, rock flour.

crater a fossil horse, long extinct in North America, was discovered buried in material deposited within the crater proper (43). The origin has thus been pushed backward many thousands of years. The crater was formed from 22 feet of Cenozoic sediments overlying nearly 200 feet of Cretaceous strata.

Crater No. 2 lies near by. It has been rather completely excavated and was found to have been, originally, 70 feet in diameter and 17 feet deep. The pit does not go down to bedrock but is entirely surrounded by incoherent material. A maximum of 6 feet of fragmental rock fell back into this crater, probably from No. 1.

The sectioning of this pit has proved to be of prime importance. Approximately one thousand small meteorites have been recovered from the layers of material immediately underneath the crater. Many more still remain buried. Estimates of a total weight of six tons of meteoritic material

have been made, but this seems rather high. It has been suggested (43) that No. 2 was formed by the combined energies of a swarm of small masses, but this seems improbable because the ballistics of small masses are far different from those of larger size. If the meteorites which produced the three known craters differed greatly in mass, they would not have landed so close together. It seems more probable that crater No. 2 was formed from the impact of a single body, which then exploded, driving numerous smaller fragment masses from a few inches to 3 feet or more into the bottom and sides of the crater. The pit thus represents a transition type in which much of the meteoritic material remains in the pit.

A third crater, much like No. 2 but smaller, has also been identified. Magnetometer surveys show several other magnetic highs, so there may be other small craters near by.

The Odessa group was produced by the collision between the earth and a small cluster of meteoritic masses. As will be seen, many of the other recently discovered meteoritic craters occur in bunches, hence it may confidently be inferred that numerous small swarms of metallic bodies, probably held together by mutual gravitational forces, travel together through space.

THE KANSAS CRATER

A small buffalo wallow near Brenham, Kansas, was excavated in 1933 by Nininger (44), that tireless searcher after craters, meteorites, and meteoritic information. It turned out to be a real meteoritic crater, 10 feet deep and of oval shape, 56 feet long and 36 feet broad, with the long dimension lying WNW. to ESE. Nininger found, within the crater, several meteorites weighing up to 125 pounds, along with hundreds of small partly oxidized meteorites.

THE ARGENTINE CRATERS

At Campo del Cielo in the Gran Chaco of Argentine is a large group of small meteoritic craters which Watson (13) says may turn out to be the world's largest group. Occurring in a region of many depressions and small lakes, the recognized craters range from 20 to 254 feet in diameter but are filled in with debris until they appear as round, shallow depressions, with the rim of the largest having been eroded so that it rises only 4 feet above the surrounding pampa. Laguna Negra occupies this pit. On the surface many pieces of large and small meteoritic iron, the largest

weighing about fourteen hundred pounds, have been found since the discovery of the craters in 1576.

One of the craters, 175 feet in diameter and 16 feet deep, has been partially excavated. Beneath it were found "white ash" and "transparent glass" and small bits of nickel iron. These, of course, are identical with the rock flour and silica glass which are standard materials at other meteoritic craters.

As Spencer notes, "There are other suggestive features worthy of investigation in this district. Many small lakes and pozos are scattered around; and in particular a chain of small lakes extends southward from the spot where the large masses of meteoritic iron have been found for a distance of nearly 100 miles into the province of Santa Fe" (45).

THE AUSTRALIAN CRATERS

THE CRATER GROUP AT HENBURY

The fall of the Karoonda meteorite on November 25, 1930, in central Australia led to the organization of an expedition under Professor Kerr Grant. This expedition brought back word that natives had found fragments of meteoritic iron surrounding several crater-like depressions near the Henbury Cattle Station. The number of craters was variously estimated as three and five. When this information became available, the South Australian Museum commissioned A. R. Alderman to survey the area.

Alderman visited the site and gathered as much pertinent data as possible. From his report it is evident that the view of the craters is decidedly unimpressive. They lie in an arid region, and from a distance the only indication of the craters is the presence of green mulga trees. In spite of the paucity of rainfall, only about 6 inches per year, the inwash of rain has partially filled them up. The finer sediments formed a hard, almost impervious layer which holds water longer than normally. As a result the mulga trees, which are usually confined to the water courses, grow in several of the craters, aiding in their identification.

Brief descriptions of each of the thirteen recognized craters follow. They are numbered according to Alderman (46), who predicts that there are additional pits still to be found. All the craters lie in a square one-half mile on the side.

The Henbury series, modified as it is by erosion and infilling, beautifully demonstrates the transition from a small crater formed by simple splashing or gouging of the ground to the true explosion crater in which the meteorite is broken up into small bits, most of which are backfired out of the crater.

Crater No. 1 has been completely removed by erosion. All that remains is a clay-pan floor and numerous surrounding fragments of nickel iron. It was probably circular and about 75 feet in diameter.

Crater No. 2 was similar to No. 1 but slightly larger. It may have been 90 feet in diameter.

Crater No. 3 is larger, being 135 feet in diameter, and still shows a slightly raised rim. The pit has been largely filled in but is still 10–18 feet deep. Within the crater a thirteen-pound meteorite was found, and near by lay 160 fragments, many of which were small. Eighty per cent of these masses were found to the west of the depression.

Radiating outward from the crater walls into the plain for about 90 feet can be seen five or six low ridges of sandstone, apparently identical with that found anywhere in the neighborhood (Ordovician age). They are a few inches high and consist of small blocks whose surfaces are blackened due to weathering, hence they may be easily distinguished from the prevailing reddish color of the surroundings. Traces of similar ridges may be seen around other craters, particularly No. 4, but in no case are they as well defined as at No. 3.

Crater No. 4 is identical with No. 3. Of about five hundred fragments of nickel iron associated with this crater, four hundred lay to the west. One hundred of these were in an area 6 feet square. This suggests the breaking-up of a larger body.

Crater No. 5 is the same size as No. 1, which it much resembles, except that low walls, 4 feet high, still remain. A shaft sunk in this crater passed through 8 feet of fine soil before coarse rock fragments, apparently washed in from the walls, prevented further digging.

Crater No. 6, known as the "water crater," is roughly circular, 240 feet in diameter and from 12 to 25 feet deep, and is the larger of two adjacent to the main crater, No. 7. A water course, normally dry, has broken through its walls, and after each rain the crater is flooded, the moisture being retained for some weeks. Mulgas and acacias, larger than usual, grow in the pit. Some of the latter are 45 feet high and 21 inches in diameter.

The walls of the water crater are highest on the side abutting the main crater.

Crater No. 7, the main crater, probably should be considered as being two craters formed by the nearly simultaneous impact of the two largest meteorites, for it is oval, 660 feet by 360 feet at the surface. The depth averages 40–50 feet and, in places, is 60 feet but quite obviously was once much greater. The walls are of the usual form, steep near the summit and with talus slopes at the foot. They are mainly formed of shattered and crushed fragments of sandstone and slaty rock, varying from the finest rock flour to large blocks several cubic feet in volume.

Black, glassy material was found north of the main crater. Alderman described it as being like the glass of fulgurites (lightning tubes), vesicular in some cases, containing rock fragments in others. It is certainly heat-fused rock, the silica glass so well known at other meteoritic craters.

Relatively few metallic fragments were found on the surface near the larger craters. A small number were near the silica glass from the main crater, but probably most of the pieces were covered up by erosion from the rim. Most of those which were found were in the water courses.

Crater No. 8 is large and well defined although rather shallow. It is about 175 feet in diameter but is only from 3 to 15 feet deep. Like No. 6, the walls are highest on the side next to the main crater.

Crater No. 9 is ill defined and doubtful. The topography suggests a small crater.

Crater No. 10, like Nos. 11, 12, and 13, is situated on a low ridge of sandstone to the south of the larger craters. It is circular, about 60 feet in diameter, with low walls.

Crater No. 11 is small and circular, about 45 feet in diameter. It has been partially excavated without the finding of any iron.

Crater No. 12 is very well defined. Although it is only 60 feet in diameter, its walls still reach 12 feet on the highest side, the one toward the ridge.

Crater No. 13 is small and rather indefinite. It is about 30 feet wide and only 3 feet deep. Bedford, in 1932, found four masses of 292, 120, 24, and 5 pounds in this pit, buried 7 feet below the bottom under broken blocks of sandstone. This is the first instance of a considerable mass of meteoritic iron found buried in a crater. It clearly represents a case in which the

mechanical impact rather than the subsequent explosion produced the crater. Bedford showed that all four pieces came from one mass.

About two thousand pieces of nickel iron have been collected over the entire region by various men. The 292-pound mass is the largest. The majority of these fragments is curiously twisted. Etched sections of these show that the bands of the lamellar structure are bent and crumpled. The pieces were undoubtedly torn from larger masses by the force of the explosions which made the craters. Larger pieces with the normal pittings of meteoritic irons are seen in etched sections each to consist of the usual large crystals. The normal lamellar octohedral structure (Widmanstätten figures) extends up to the very edge of the mass without any granulation of the kamacite. This clearly proves that these masses are merely the weathered remains of still larger masses, the cores of which had not been raised to a temperature of 850° C. by the conduction of heat from the outside. It shows that meteoritic collisions happen so rapidly and are so violent that most of the matter in the explosion region is either vaporized or else not seriously heated. Very little liquefaction occurs.

No one knows how old these craters are. Trees hundreds of years old are found in the pits. Some of the meteorites have been completely oxidized, which implies a great age, as the climate there is extremely arid. Bedford suggests that the craters are not ancient. Alderman believes that they are thousands of years old, and yet the natives seem to have a tradition that they were produced in a fiery explosion, for they call the place "Chindu chinna waru chingi yaku," which means "Sun walk fire devil rock." Old blacks would not camp within a couple of miles of the craters. How long such a legend would be handed down is a moot point, but there does not seem to be any way for the natives to associate light and fire with these depressions in the ground unless their ancestors actually had witnessed the landings and resultant blasts.

THE BOXHOLE CRATER

In 1937 another large but ancient meteoritic crater (47) was found in Australia about 200 miles northeast of Henbury. It apparently is similar to the main crater at Odessa, being about 600 feet in diameter. The pit has been filled in until it is now only 50 feet deep, i.e., probably about half its original depth.

Shale balls, meteoritic fragments, and a 180-pound meteorite have been identified near by; otherwise practically nothing is known of this fall.

THE DALGARANGA CRATER

A smaller crater (48), 230 feet wide and only 16 feet deep, was located in 1923. Around the rim, primarily on the northwest side, the rock layers have been shattered and tilted up. Many of the meteoritic pieces found near by had been warped and twisted in a manner reminiscent of those at the Henbury fall.

THE EURASIAN CRATERS

THE ESTHONIAN CRATERS

On the large Baltic island of Oesel another of the groups of multiple craters is found (49). The largest of the six pits, the Kaalijärv, appears as a wooded knoll, 20–25 feet high. Beyond the tree-covered rim, the crater itself becomes visible. It is nearly circular with diameters ranging from 300 feet to 360 feet. Much of the crater is filled with a lake 200 feet across, so a careful study of the pit has not been made. It appears to be about 50 feet deep, rim to lake bottom, and it is known that the underlying rock layers are shattered.

The Kaalijärv has been known since 1827, and many bad guesses have been made as to its origin. Some of the earlier thoughts were that it was a man-made battlement, a karst weathering of limestone, or even that it was produced by the solution of salt in a salt dome. These wild guesses completely ignored the fact that the region showed all the characteristics of a crater born in a violent explosion. It has the upraised rim with steep inner and gradual outer slopes. There are numerous blocks of rock and other shattered ejectamenta, and the local rock strata have been upraised until they dip radially outward at angles up to 30° or 40°.

The normal geologic structure of the island is that of horizontally bedded Silurian dolomite with a covering of glacial deposits. The fact that the meteorites landed in this material may have hindered the recognition of the true nature of the craters. No silica glass has ever been found, owing, of course, to the absence of quartz in the dolomite. The pits are certainly of postglacial age.

For many years no meteoritic materials were found, but in 1937, after ten years of effort, Reinwaldt completely established the meteoritic nature of the craters by finding 28 small fragments of nickel iron totaling 110 grams. As the island has been inhabited for many centuries and extensively cultivated, it is not strange that all surface metals have long since disappeared.

Near by, in an area of less than one-half a square mile lie five other smaller craters and at least three other depressions which have been filled in with stones from farmers' fields. Four of the craters are circular, 120, 100, 65, and 35 feet in diameter. The other is oval, 175 feet by 120 feet, and is probably a double crater much like the main crater at Henbury. Several of the smaller craters have been excavated. Two tiny meteorites were found in the smallest crater, the others in the oval one. Beneath the 65-foot crater was a funnel-shaped hole, 4 feet wide and 2 feet deep, blasted into the limestone. The adjacent rocks are cracked and have a burnt appearance.

THE ARABIAN CRATERS

Almost lost under the shifting sands of the Great South Desert of Arabia in the Rub' al Khali (the "Empty Quarter") are two of the most unusual meteoritic craters yet found. They were discovered by Philby (50) in 1932 in his epic search for the "lost city" of Wabar. There never was any question of the nature of these queer depressions, for Philby reported the finding of many rusted nickel-iron fragments, the largest having a mass of twenty-five pounds. Laminated iron shale in which sand grains are cemented also occurs. The smaller pieces of meteoritic iron when sectioned, polished, and etched show a partial destruction of the characteristic structure such as can be brought about artificially by heating the material to about 850° C.

The larger of the two known craters at Wabar is 328 feet in diameter and although partially filled with sand is about 40 feet deep. The other, less than one-half mile distant, is oval in shape, 180 feet by 130 feet, and is perhaps 30 feet deep. Nothing is known regarding the underlying rock layers. At least two and possibly other pits exist, covered by the ever moving dunes.

The rims of both craters seem to be built up of silica glass which is highly vesicular, in appearance like cinders or iron-furnace slag. This material clearly is not volcanic in nature. Microscopic examination of the glass discloses numerous small specks ranging from 0.14 mm. downward. They give a metallic luster by reflected light. There are usually from one to two million per cubic centimeter. Analysis indicates that they are actually little globes of nickel iron. Spencer (45), formerly keeper of the minerals in the British Museum, concluded that these tiny spheres were formed in an atmosphere from which the oxygen had momentarily been

eliminated and then drizzled down into the boiling silica. As there is very little moisture in the Wabar Desert sands, the vesicular nature of the glass must also have been due to the boiling of the silica. Additional evidence of the extreme temperatures generated here is found from the dew-like drops of condensed silica on the glassy surfaces. Table 1 is of interest in this connection. At the high pressures which probably existed the corresponding figures were possibly somewhat higher.

At no other meteoritic crater is there any comparable evidence of liquefaction on such a large scale. It may also be noted that in no other known case did a meteorite land in deep, loose sand. The incoherent nature of the sand may be the factor which led to the generation of so much local heat.

TABLE I

CRITICAL TEMPERATURES

	Degrees Centigrade
Nickel melts	1,452
Iron melts	1,535
Silica melts	1,710
Nickel boils	2,900
Iron boils	3,200
Silica boils	3,500

Wabar is a legendary city mentioned in semiclassical Arabian writings as having been "destroyed by fire from heaven." It seems entirely probable that the "ruins" are the craters and the "cinders" the abundant silica glass. Perhaps here, too, is an ancient race memory of the meteoritic fall.

THE SIBERIAN CRATERS

In the early morning of June 30, 1908, the inhabitants of the north and east portions of distant Siberia were privileged to witness the only fall within historic times of a group of meteorites large enough and moving fast enough to blast craters in the ground. Strangely, in spite of the magnitude of the fall no large expeditions were organized to investigate the region till 1928—it must be admitted, however, that the first World War and the Russian Revolution occupied a part of the interval. In that year the Russian scientist Kulik studied the craters, at the head of a small expedition. In 1930–31 he spent thirteen months at the site.

In *Science* for May 11, 1928, Dr. George P. Merrill of the United States

National Museum reviewed Kulik's original report, which was printed in Russian. A portion of the article is given here:

The appearance at seven o'clock in the morning on June 30, 1908, of a "fiery body" of unusual brightness rolling across the sky out of the northeast and falling down in the "taiga" between the Yenissei and Lena rivers, north of the railroad line [about 500 miles north of Lake Baikal in latitude 61° N., longitude 102° E.], was observed by a great number of people, mostly the native inhabitants living in the basins of of these rivers.

The fall of the meteorite was instantly followed by a column of fire rising skyward, by the formation of heavy black clouds [a column pillared up from 12 to 15 miles into the atmosphere], and by a most deafening, resounding noise far surpassing in its magnitude any thunderstorm or artillery cannonade. This was heard for hundreds of kilometers within a radius of the cities of Yenisseisk, Krasnojarsk, Kansk, Nijnedinsk and Kirensk on the Lena. [This immediately brings to mind the atomic bombs dropped on Hiroshima and Nagasaki and Bikini. The bombs, while less powerful than the meteorite, caused similar effects.]

A terrific air wave was formed which pushed ahead everything that it met in its way. The water in all rivers, lakes, and streams was raised up; people and animals were lifted by it and carried along.

The vibrations produced by the fall of the meteorite were detected and registered by the seismographs of the Physical Observatory at Irkutsk, where Mr. A. V. Vesnesenski, who was in charge of the Observatory, calculated the epicenter of the "earthquake" to be located in the upper part of the Podkamennaya Tunguska.

The phenomenon produced considerable panic, especially among the natives living in the basins of the Yenissei and all the various Tunguska rivers and adjacent parts of the Lena River Basin.

Several attempts made in 1908 to find the body of the meteorite were fruitless as for some reason all parties were searching near the city of Kansk and not in the locality determined by A. V. Vesnesenski, whose observations unfortunately remained unpublished. Gradually interest in the new meteorite was almost forgotten, except as a tale among the natives.

In 1928, Mr. L. Kulik attempted to find the exact location of the meteorite and led an expedition to the Tungusk region. Owing to the lack of funds and the extreme difficulties of transportation in the wilderness of taiga and tundra, the expedition was not altogether successful. However, Mr. Kulik was able to reach the area where the taiga bore distinct traces of the passage of the meteorite. An area struck by the meteorite is a water table between the upper part of the Podkamennaya Tunguska and its right tributary, the river Chuni. The area is largely covered with tundra in the process of formation, intersected by hills, small lakes, swamps and typical tundra. The immediate area is surrounded by high naked hills, deforested by the falling meteorite. All the trees are still on the ground, their tops spread out in fan-like fashion away from the central zone of the fall. Exceptions are noted only in the ravines or in the gorges and deep perpendicular valleys and also in a zone which can be considered as the interference zone. And even in these places the trees, in most cases, are scorched and dead.

The zone where the heat effect of the meteorite is evident is considered by L. Kulik

to be thirty kilometers in diameter and the area of the air wave breaking the trees is fifty kilometers in diameter.

The center part of the "fire zone" is covered by shallow, funnel-shaped craters, reaching in some instances many tens of meters in diameter and not greater than four to five meters in depth. The bottoms of the craters are covered with swampy growth.

Unfortunately, Mr. Kulik was not able to find the body of the meteorite or determine the depth to which it had sunk.

He believes that the meteorite of 1908 was an aggregate of meteors, moving with a rate approaching seventy two kilometers a second. Some of the aggregates undoubtedly exceeded one hundred thirty tons in weight. Hot gases (above one thousand degrees C) surrounded the meteorite and started fires before the meteorite had reached the ground and sunk into it, forming craters, uprooting trees, and burning everything that can burn in the center of its fall.

Other stories of the fall tell of the engineer of the Trans-Siberian Railway, over 400 miles to the south, who stopped his train because he feared that the vibrations of the "earthquake" would shake it off the rails. Still nearer the scene, the house of a farmer, Semenow, was demolished and he himself knocked unconscious. All this 50 miles away. A herd of reindeer at the place of fall was completely wiped out, only a few charred carcasses remaining.

Watson (13) makes the interesting point that if this meteorite had met the earth just four hours and forty-seven minutes later, we should have known of the blast much sooner, for it would have scored a bull's-eye hit on the city of St. Petersburg, now called Leningrad.

At the Kew Observatory in England at 5:30 P.M. on the day of the collision a series of unusual pressure waves in the atmosphere was found on the records of the microbarograph. Whipple (51) calculated that the rate of travel of sound is such as properly to account for the difference in time within a quarter of a minute. European seismographs recorded a strong ground wave. Both sound and shock waves were observed at many Siberian stations. Estimates of the energy expended range around 10^{21} ergs (51). LaPaz (123) has suggested the possibility that it might be as high as 10^{24} ergs, but Whipple's determination of the energy in the air waves does not permit this interpretation. It appears that about five thousand times as much energy went to make air waves as went to make earth waves. We are led to the conclusion that the Siberian craters are too small in comparison with the energies released. Is it possible that the meteorite or meteorites burst in the air just before they struck the ground or, more probably, that the explosion was an air burst immediately after a ricochet.

The low angle of fall, about 17°, would almost require a ricochet, judging from artillery experiments of the United States Army. An explosion above ground would be in full accord with the ratio of energies found in the air and ground waves and also would obviate the necessity of postulating that a swarm of meteorites caused the damage. A single body exploding in the air could produce the numerous craters observed simply by the scattering of high-energy fragments.

A rough estimate of the meteoritic mass may be made from the energies liberated in these waves and the destruction surrounding the craters. A value of a few hundred tons results.

Kulik found a total of at least ten craters, possibly two hundred, ranging from 30 to 175 feet in diameter. They are water filled, and marsh growths partially cover them. In his 1930–31 stay he excavated one crater, finding the customary rock flour and fused quartz containing minute grains of nickel iron. Around the area of these craters the peat is thrown into concentric ridges. A trench cut through one of these ridges showed contorted folds of peat, clay, and ice. Because of the swampy nature of the land, the surface features, craters, and broken trees will completely disappear in a few hundred years, leaving only the legends and the printed page to record this tremendous paroxysm.

An interesting side light has been raised in recent years by Rojansky (124) and LaPaz (125). The former suggested the possibility of the existence in outer space of contraterrene meteorites. This strange and hypothetical matter would consist of a nucleus of "negative protons" surrounded by positrons. Possibly neutrons would replace some of the "negative protons." When such an atom strikes normal, or terrene, matter, the opposite forms mutually destroy each other—converting their entire masses into energy.

LaPaz has intimated that the Siberian meteorite was contraterrene in nature because of the great amount of energy expended, the relative insignificance of the craters, and the absence of nickel iron positively attributable to the meteorite. Kulik did, however, find some nickel iron in the fused silica glass. This probably did come from the intruding mass.

Rojansky (124) states:

> If we disregard the effects of heating and make the rough assumption that a contraterrene meteor annihilates all the air molecules which it would strike if it did not affect their motion, we find, for example, that unless the initial top-to-bottom dimension of

a contraterrene iron meteor, falling vertically without tumbling, exceeds 130 (i.e., $76 \times 13.6/7.9$) cm, the meteor would be entirely radiated away before reaching sea-level.

Since we cannot assume a nontumbling meteorite, we must postulate a spherical mass of contraterrene iron, 130 cm. in diameter, as a minimum size to allow our contraterrene meteorite to reach the ground in a vertical plunge through the atmosphere. As the Siberian meteorite traveled at an angle of about 17° to the horizontal, the air mass penetrated—and, hence, the minimum allowable mass of the meteorite—must be tripled to prevent complete radiation before the body reached the ground. However, because of the possible presence of neutrons in the meteorite, the original smaller mass will be assumed to be correct.

A sphere of contraterrene iron, 130 cm. in diameter, would have a mass of 9×10^6 grams. Upon contact with air this body would disintegrate into 8×10^{27} ergs of radiant energy, which must be doubled to account for the equal mass of air destroyed in the process; this yields a total energy release of over 10^{28} ergs during the passage of the body through the air. Such a tremendous amount of energy is more than ten thousand times the highest estimate made of the energy of the Siberian meteorite and more than ten million times the most probable value of the energy actually released at the impact.

Consequently, the conclusion is reached that it is highly improbable that the Siberian meteorite was composed of contraterrene matter. It was simply a normal meteorite much larger than is usually encountered.

Of the preceding craters there is none whose origin is now questioned.[2] All were formed in the same manner; yet of these structures both the Arizona crater and the group in Oesel were known for many years before their nature was proved. May it not be so with other craters which are now known but whose past histories are shrouded in doubt or wrongly translated?

THE PRETORIA SALT PAN

This strange depression lies in the wooded, gently rolling Bushveld of the Transvaal about 25 miles north-northwest of Pretoria. The surrounding-country rock is the red Bushveld granite, nearly level, with isolated outliers of grit from the Coal Measure series of the Karroo system.

2. It has been reported recently (121) that a small crater on Amak, an island in the Aleutians, is probably of meteoritic origin and, also, that on February 12, 1947, a cluster of meteorites struck in eastern Siberia, blasting craters up to 75 feet in diameter.

The great hollow is almost perfectly circular, with diameters north to south of 3,460 feet and 3,330 feet measured at right angles. The circumscribed ridge rises an average of 100 feet above the level of the neighboring country with a peak of 200 feet on the northwest side. It is composed of coarse, uncemented breccia made up almost exclusively of large and small angular granitic blocks resting on Karroo grits. The inner slope is steep, the outer gradual. It clearly is in exactly the same position as that in which it fell after being blasted from the pit. Among the fragmental masses there is not to be found a single specimen of young volcanic rock. Many of the granite blocks are traversed by narrow fissures filled with a breccia composed of angular fragments of quartz and feldspar.

The floor of the crater lies 300 feet below the rim and presents a strange appearance. The outer portion is generally covered by a dazzling white saline incrustation while a dark pool of soda-salt brine fills the center. Bore holes have been forced down through 230 feet of bedded layers. In the central portion the 18 feet of the Trona-Mud zone are above the Gaylussite layer of permeable beds made up largely of Gaylussite crystals interbedded with and underlain by saline clays and marls. These layers are impregnated with clear, saturated soda-salt brine. It is upon this brine that the soda industry established at the Pan is based. There is evidence to show that the liquor has been and is being generated by underground water that has forced its way into the caldera deposits from above.

The divisional planes of the granite as exposed in the walls dip radially toward the pit, but cross-sections through the rim show definitely that there exists a ring anticline, with the upthrow occurring approximately under the eroded rim. The proponents (52) of a volcanic origin for the Salt Pan claim that there was (1) updoming of the Bushveld granite and overlying grits over the scene of eruption, (2) drilling of the vent by a great phreatic explosion or succession of such explosions, and (3) subsidence by faulting and slumping of the interior of the volcano within a ring-shaped fault.

The alternative meteoritic hypothesis accounts for the updoming by the force of the explosion and the inevitable rebound after the impact. The anticline could have been produced, like that at Odessa No. 1 and elsewhere, by the tangential thrust of the near-surface explosion. No subterranean vent has yet been found.

The Salt Pan is decidedly of post-Karroo age; and, judging by the pres-

ent well-preserved condition, it is young, certainly post-Cretaceous and probably of late Quaternary age.

There is no obvious reason for its being situated where it is, for it is not visibly connected with any line of fissure or faulting, having apparently been formed independently of any plane of structural weakness in the earth's crust. Rohleder concludes: "Nothing whatever suggests volcanic origin, but the parallelism with a meteor crater is obvious" (53). Spencer (45) has also made the same suggestion independently. It seems highly probable that this crater, only slightly inferior to that in Arizona, was produced by meteoritic impact, possibly by a vast stony mass. No nickel iron has yet been reported from this location. Whether or not it has been searched for is not recorded.

THE ASHANTI CRATER

In the Gold Coast of Africa lies a peculiar structure which has caused many a scientific argument to rage. A vast crater, variously reported as $6\frac{1}{2}$ miles in diameter or 7 by 9 miles across, is partially filled by Lake Bosumtwi. The lake measures 5 miles in diameter and has a maximum depth of 238 feet. The waters are self-contained, and there is no other lake within 500 miles.

The inner rim of the caldera is precipitous, rising from 1,000 to 1,500 feet from the lake. The walls are jungle clad, and the pit is surrounded by a tropical forest which makes all study of the region difficult. The crater is bounded by a peripheral depression which separates the actual rim from a concentric ring of elevations. The width of the depression is $\frac{1}{2}$–2 miles.

Maclaren (54) originally suggested that the crater had a meteoritic origin, but this has been disputed by Rohleder and Junner. No nickel iron has ever been found, with the possible exception of a specimen reputedly picked up over half a century ago on the shore of the lake.

Rohleder (55) reported that the planes of schistosity of the metamorphic (pre-Cambrian) rocks on the inner walls of the caldera dip radially inward and that the dip gradually reverses itself until beyond the concentric depression the layers show a diminishing outward dip. He believes that the region was broadly uparched before the center collapsed to produce the caldera. Junner (56), however, has cast grave doubts on these structural studies.

Both Junner and Rohleder base much of the assumption that the crater

is of igneous origin upon the finding of a few relic patches of pyroclastic debris on the inner walls. This debris, according to Junner, consists in large part of comminuted granite and phylitte, opaline quartz, and dacite pitchstone in a matrix of glassy pumice. Accompanying it are scattered masses of breccia supposedly produced by the shattering of local rocks along faults. These extend to a distance of 7 miles from the center of disturbance. Junner concludes that the succession of events was as follows: First a doming of the crystalline crust by a laccolithic injection; then an upward and outward thrusting of the crushed rocks by gas pressure, culminating in several explosions which blasted a funnel-shaped crater and ejected a little gas-rich magma, together with great quantities of lithic debris; and, finally, an engulfment caused by the loss of gas and consolidation of the magma body. That subsidence has continued since the catastrophe is clear from the fact that the lake sediments on the lower walls of the caldera show an inward dip.

Hence we are left on the horns of a dilemma. It is apparent that an explosion did occur, but the origin of the explosive force is under debate. It is also true that a subsidence followed the blast. Junner has outlined one reasonable hypothesis; but may it not be equally reasonable to expect a certain amount of settling within the ring faults produced by the impact of a meteorite and the subsequent rebound of the rock layers? More data are needed before a satisfactory solution to the problem can be reached.

THE KÖFELS "CRATER"

In 1936 Suess (57) proposed a meteoritic origin for the Köfels "Crater," a curious widening in the Oetz Valley of the Tyrolian Alps. He found no meteoritic materials but did identify a peculiar pumice which apparently was derived by fusion of the gneissic country rock. On the suspicion that this pumice was actually meteoritic silica glass, Hammer (58) analyzed samples of it but reported that there was no evidence of nickel iron. The gneiss is locally fractured and brecciated, and the depression shows signs of having been formed by violent explosive forces. The form of the "crater" is irregular, which may be expected from the normal rugged nature of the region. There are no volcanic rocks at Köfels and no recent vulcanism. Schmidt (59) says, contrary to Suess, that there is evidence of tectonic movement in the region, and therefore the lack of such move-

ment cannot be used as a criterion against the volcanic origin of the crater.

Again there are not enough facts available to allow a decision to be made. It would be extremely interesting if the Köfels were to prove to be of meteoritic nature, for it would thus become the first recognized case in mountainous land.

SUMMARY

Sufficient meteoritic craters are now known and have been minutely examined so that we have a rather good idea of the structural sequence. They are always circular, or nearly so, with upraised rims and bottoms depressed below the normal ground-level. Except for the pushed-up rock layers, the rim materials are essentially equal in volume to the portion of the pit below the ground-level. In the very smallest craters, up to about 30 feet in diameter, the process is purely one of splashing and gouging of the ground by the mechanical impact. The meteorite may not be shattered and may remain in the pit. As the size of the crater increases, evidences are found that there is a progressively greater fragmentation of the meteorite, much of which is backfired out of the crater, although drill holes sunk into the Arizona crater show definitely that rather large masses of nickel iron remain buried underneath.

In every one of the ten positively identified meteoritic craters or groups of craters nickel iron is found. In no case is there a recognized crater due to the impact of a stony meteorite, and yet stony meteorites are about five times as numerous as the metallic type, at least in the smaller sizes. No stony meteorites are known which are much heavier than one ton.

There seem to be three possible explanations. It is conceivable that there are no large stony meteorites or, perhaps, that they are extremely rare. A more likely theory is that the stones of large size disintegrate high in the atmosphere from the terrific stresses and strains set up by the air's resistance. The most likely possibility is that the large stones do exist and do hold together down to the ground. If this is true, then there must be meteoritic craters formed without benefit of nickel iron. Whipple was probably the first to suggest this.

Small amounts of silica glass are formed at most craters from quartzitic rocks, the paucity of this material probably indicating that the extreme rapidity with which such craters are formed prevented much liquefaction

of matter; it was either relatively unheated or else vaporized. The most obvious material formed in each case is rock flour—powdered rock. Part of this often stays within the pit, but much is ejected.

Little is known of the nature of the subcrater rock layers, but logic would infer that they must be displaced somewhat by compression and rebound as well as brecciated and that shock waves have been transmitted by them. These effects naturally should increase with increasing size of the meteorite and hence with increasing crater size.

The strata which have been shattered and are now exposed in the crater walls are invariably tilted so as to dip radially outward. In some cases they have actually been overturned. Often these strata show distinct bilateral symmetry with opposed points of maximum and minimum uplift.

The rims are always raised except in the older craters where erosion has destroyed them. The inner slopes are relatively steep, while the outer portions gradually sink to the undisturbed level at a distance of perhaps one-quarter to one-third the diameter of the pit. The rim and outer slope are often marked by blocks of stone, large and small, hurled from the rock layers smashed at the impact.

The crater bottoms, without exception, were depressed below the ground-level at the time they were formed, and their depths bear a roughly constant relationship to their diameters.

Only ten authenticated meteoritic craters or groups of craters are known. All were discovered after 1827, and seven, perhaps eight, were found after 1921. Many more must be distributed over the earth; they are now being identified at the rate of one every three years.

In the areas of high rainfall the craters quickly disappear. Many must have been covered by glacial deposits or desert sands. Many regions are almost or entirely uninhabited. Watson (13) estimates that meteorites capable of producing craters 30 feet or more in diameter strike the earth once each century.

Let us assume that the ten groups now known actually constitute all the craters formed in the last fifty thousand years and that therefore one crater or group of pits is formed each five thousand years. If the rate in the past were the same, each area of 125 square miles would have been struck at least once in the last 2,000,000,000 years, a total of four hundred thousand craters or crater groups distributed throughout the lithic layers. Such an area is smaller than the average American county. Although this

figure is almost certainly a minimum value, it approaches the observed density of very small craters seen in the moon.

Three out of four such meteorites, perforce, fall into the ocean and hence leave no trace. Nininger (39) has described a great procession of fireballs appearing in 1913 over western Saskatchewan. It consisted of from six to ten groups of bolides of four to six members each. They appeared as bright as Venus, perhaps brighter, when first seen. Over Ontario they were still more brilliant. "Detonations and earth tremors were caused along their pathway to a distance of twenty to seventy miles on either side."

Clouds obscured the display to observers in the eastern United States, but from many ships on the Atlantic passengers watched it become increasingly spectacular. It was seen from Bermuda, and the meteorites seem to have plunged into the sea somewhere southeast of the islands. According to all descriptions, this swarm of fireballs was far more impressive than those of the Siberian fall, five years earlier.

How many other gigantic meteorites have disappeared into the watery wastes?

What myriads of meteoritic craters lie unseen on the surface or for ages hidden in stony crypts?

CHAPTER 5

Fossil Terrestrial Meteorite Craters

EVER since the first promulgation of the theory that the craters of the moon were caused by the impacts of myriads of meteorites, large and small, men have realized that for the moon to have undergone such a bombardment implied that the earth, of necessity, had also suffered an equal proportion of these colossal blows from space. It is not difficult to show that each square mile on either earth or moon would receive essentially the same numbers of meteorites. The masses of the earth and moon do not enter into the problem to a first approximation.

Such being the case, the cry arose, "Where are the great meteoritic craters of the earth? Why do we not find them?"

For years not a single example of such a crater was recognized. Many scientists accepted the fact that none had been recognized as proof that no such craters existed or had ever existed. This was hardly a scientific attitude, but for a long time it was used as a primary argument against the meteoritic theory and for the volcanic hypothesis. To this day there is no geologic structure generally accepted as a fossil meteoritic crater. Dozens of small modern craters are known, but none of the ancient gigantic pits can be seen, nor do scientists agree that any geologic structure is proved beyond a doubt to be an old meteoritic scar.

At this point it is relevant to pause and recall that in the past the moon and earth have developed along divergent paths. The moon is practically a dead body and has been so throughout much of its history. If a crater were formed there in, say, Silurian times, it would still be there, much as it was originally, unless, perchance, another crater were formed later and overlay the former. Many of the early craters have been drowned by the great lava flows, but, except for these, the face of the moon, once marked, remains pitted.

On the contrary, the earth's geologic history is a record of rising and

falling lands, advances and retreats of vast epeiric seas, mountain building, faulting, folding, erosion, and deposition. All of these must affect the record of ancient conditions as transmitted to us. Rare indeed is the surface of land which has descended without major change since even as recent a geologic time as the Cretaceous. What chance, then, is there for geologists to identify a meteoritic crater of Archeozoic or even of Cambrian age?

The answer to the foregoing is that it would require an almost impossible series of events to have occurred for a complete fossil crater to have been preserved. All the normal features usually associated with a meteoritic crater would probably have disappeared—the pit, rim, nickel-iron fragments, ejectamenta, the tilted and brecciated rocks. All that could reasonably be expected to remain would be the basement structures, the modifications produced deep below the earth's surface by the unimaginably great pressures which developed as the intruding mass came to a halt and exploded.

These are the formations which must be sought out by geologists. These are the formations which must be present on and in the earth if the moon's craters are meteoritic in origin.

Two men, Boon and Albritton (60), have begun an investigation into this problem by deducing just what effects would be produced in the earth's crust beneath a meteoritic crater and then finding that similar structures exist and that for these structures no ordinary geologic process is known to be capable of giving a completely satisfactory explanation. Unfortunately, their work is so recent that it has not had the wide circulation it deserves; and, consequently, the opinions of most of the world's geologists and geophysicists have not been recorded, but it is significant that no serious criticisms have been raised.

It may turn out that the structures to be described have no connection with the meteoritic problem; but, even in the event that they are proved to be terrestrial in origin, the search for the vast ancient meteoritic scars will continue. It is amply clear that the earth is being bombarded at the present time by masses large enough to produce small craters. It is highly illogical to assume that these bodies started falling only recently. It is highly probable that throughout geologic history impact craters were formed and that mixed with the small meteorites were larger ones similar to or part of the lesser asteroids.

Recent astronomical discoveries have somewhat expanded our usual mundane viewpoint. Several small asteroids have been observed to approach perilously close to the earth. In 1898 Witt of Berlin found Eros (433) which at times comes within 14,000,000 miles. No more of this class were detected until 1911 when Albert (719) was discovered. It, too, comes well inside the orbit of Mars but was followed for so short a time that it has never been recovered on subsequent passages. Some day it probably will be found again. In 1932 the Belgian astronomer Delporte photographed Amor (1221) which comes nearer the earth than does either Eros or Albert. Apollo was found by Reinmuth at Heidelberg on April 27, 1932. It was shown to have been, on that passage, as close as 1,800,000 miles, to have a period of 1.8 years, and actually to go closer to the sun than does Venus.[1] Hence it may often be in the earth's neighborhood.

On February 12, 1936, and October 28, 1937, Adonis and Hermes were discovered, the former by Delporte and the latter by Reinmuth, just to keep the contest even. Adonis passed the earth by about 900,000 miles, while Hermes was even closer. It missed by the astronomically small space of 600,000 miles, less than three times the distance of the moon, a definitely narrow escape.

Unfortunately, Adonis, Apollo, and Hermes came so close to the earth that they flashed into view and quickly faded. Their orbits are very poorly known but, like Albert, may be picked up again on some future visit.

Except for Eros, which is several times larger, these little bodies are perhaps 1 mile in diameter and hence can be seen or photographed only when they are very near, but in order to pass close to the earth their orbits must be so oriented that these asteroids cross the plane of the ecliptic when they are at the approximate distance of the earth from the sun.

These cosmic cannon balls, each loaded, in effect, with high explosive, must be representative of thousands of such bodies. Moderately close approaches are rather frequent, as we are just coming to realize. Actual direct hits must be rather rare. Watson believes that "the earth probably goes at least a hundred thousand years between collisions with them" (13).

Each tiny asteroid would be capable of blasting a hole in the earth's crust entirely comparable to all save the very largest of the lunar craters.

1. Apollo came within 84,000 miles of Venus on this passage.

A mass considerably less than that of Eros would be adequate to produce the largest crater. At the suggested frequency there would have been twenty thousand such crater-forming impacts in the last 2,000,000,000 years. The agreement with the observed numbers of lunar craters, although not conclusive, is amazing.

The impact of a large meteorite against a rocky surface is an occurrence of such magnitude that it far transcends any and all the familiar terrestrial phenomena. Nevertheless, we may apply known physical laws and properties of matter to the problem and arrive rather closely at a broad picture of the major happenings consequent to such a landing.

Somehow or other the tremendous kinetic energy of the rapidly moving meteorite must be accounted for after the explosion. There are only four possibilities: First, the impact will shift the earth, or moon, slightly in its orbit. Second, if the explosion is violent enough, matter will be "kicked back" into interplanetary space and thus depart with some of the original energy. Third, strains may be set up in the crustal layers, some of which will be displaced, others crushed and powdered. Fourth, heat will be generated.

Loss due to point one will always occur. In the second case, if the impact is on the earth, the blanket of air and high gravitational pull will prevent matter from again reaching outer space, and the net result of the ejection of matter from the explosion pit will be the production of heat, often distant from the point of original impact. Matter from a meteorite crater could easily be hurled completely away from the airless moon. The semipermanent strains set up in the crust will account for a small part of the energy as will the changes in potential energy due to displacement of matter, but, in the long run, most of the meteorite's energy will be turned into heat; the crux of the problem is to identify where and how this heat is distributed.

It is a well-known fact that in all but two of the meteoritic craters recognized on earth there is little evidence of any great amount of heat being released upon impact. The two exceptions are the Wabar craters in the sandy wastes of the Arabian Desert where large amounts of fused silica coat the walls and bottoms of the craters. In other meteoritic craters fused silica glass is usually found, and occasionally certain rocks are metamorphosed, but evidences of great amounts of heat are lacking.

From these facts it seems apparent that much of the energy is trans-

mitted in shock waves through the crust and air and thence gradually converted into heat

Large meteorites do undoubtedly, reach the surface of the earth or moon with essentially undiminished speed Direct measurements of meteor velocities give top figures of the order of 50 miles per second Others move more slowly but even so must strike with stunning force if they are of a size capable of producing a crater It can easily be calculated that at a speed of only 4 miles per second each gram of matter in a meteorite possesses energy equal to six grams of TNT or about five thousand calories per gram, while at 50 miles per second the energy available is nearly eight hundred thousand calories per gram On impact this energy must be quickly dissipated

Except for the very smallest of the relatively few modern meteorite craters known on earth evidences of tremendous explosive activity are obvious There is always a radial distribution of both meteoritic matter and crustal rock scattered over perhaps ten times the radius of the crater proper the local brecciation of the near by rock layers and their pulverization into rock flour the occasional manifestations of intense but localized thermal metamorphism and the radially outward dip of rim rocks all lead to the conclusion that tremendous explosions have occurred at these localities and that these explosions have been caused by the impacts of meteorites

These data being granted it remains to see how the energy is dissipated For large bodies only a very small amount of the available energy of motion will be lost during the flight through the air The amount lost is measured by the difference in striking velocity and that at the instant the air resistance began with proper corrections for the acceleration of gravity This loss must be a small percentage

When a meteorite strikes the earth it encounters tremendous resistance This is the resultant of four factors The first is the rigidity of the surface layers particularly against shearing forces the second and third are resistance to compression and the amount of heat produced and the last is the inertia of the atoms and molecules in the earth as they fight to keep from being displaced For a collision with a low velocity body moving perhaps 5 miles per second or slower the resistance is largely controlled by rigidity but once the velocity becomes greater than that of the waves created in the earth s crust, then the resistance due to inertia be-

comes far and away the most powerful factor and all other resistances fade into insignificance It is easy to visualize this condition For an ordinary blow such as a hammer striking an anvil or even a bullet striking a piece of steel the elastic waves travel in advance of the impinging body Hence the molecules are set in motion and they have time to get out of the way On the other hand, a high velocity meteorite strikes with a higher velocity than the shock waves it produces the molecules are given no warning of its coming and, consequently, they are trapped in front of the meteorite The accelerations of the particles and the forces necessary to produce them become enormous

A calculation can be made which applies this principle to a hypothetical collision between the earth and a large meteorite It is assumed that the body is a spherical mass of nickel iron 250 feet in diameter, moving with a velocity of 100,000 feet per second (19 miles per second) and that the earth encountered has a density of 170 pounds per cubic foot The peak pressure created by inertia is calculated to be about 25 000 000 atmospheres or roughly ten times the calculated pressure at the center of the earth The kinetic energy at the time of impact is $3\ 2 \times 10^{24}$ ergs

At first the meteorite would plunge into the earth, moving faster than the shock waves and pushing ahead of it an ever increasing plug of com pressed rock and probably a similar plug of compressed air When the speed of the meteorite becomes less than that of the elastic waves the vast amount of compression produced finds a shoulder against which to push and the mass is soon stopped

As long as the velocity is greater than that of the shock waves very little heat is generated as heat is a measure of the random motions of molecules and atoms and these random motions are temporarily stopped during the initial phases of the impact when the tremendous meteoritic velocity is imparted to the plug It is only after the velocity drops below that of the shock waves that the phenomenon of heat enters the picture

At the instant of stopping much of the transformed kinetic energy must be stored in the highly compressed matter ahead of the bolide as the elastic shock waves could not have transmitted any great portion of it in the brief time and only a very little heat could have been conducted away Conduction of heat is a rather slow process With the stoppage of motion the meteorite is sitting on top of a tremendously compressed tre-

mendously hot plug of matter Naturally an explosion of the utmost violence follows This explosion will be directed upward at first in the direction of least resistance but as it develops and the explosive focus moves upward, the blast will tend more and more horizontally

By contrast if any large mass of meteoritic material is found to remain in a crater it implies that the body struck with a low velocity so that the resultant explosion was not violent enough to eject the meteorite The size of the meteorite necessary to account for any given crater increases as the striking velocity decreases

It may be noted that this inertial resistance is not a function of the state of matter hence water will stop and eject high velocity meteorites as well as will rock

When a large meteorite strikes the earth it deals a terrific blow to a medium which has a limited degree of freedom and a high degree of elasticity of volume While some materials such as clay have little or no elasticity of shape they all have great elasticity of volume Brittle substances are not shattered by pressure if the pressure is applied to all sides, but by tension Hence after compression they all rebound Therefore as a result of impact and explosion a series of concentric waves would go out in all directions forming ring anticlines and synclines These waves would be strongly damped by the overburden and by friction along joint, bedding and fault planes The central zone completely damped by tension fractures produced by rebound would become fixed as a structural dome

It must be admitted however that we do not know the details of the basement structures Nevertheless, the general and simplest type of structure to be expected beneath large meteoritic craters would be a central dome surrounded by a ring syncline and possibly other ring folds, the whole resembling a group of damped waves

These structures should not be radially symmetrical unless the falling meteorites struck the surface of the earth at right angles Rims of known craters commonly show opposed points of maximum and minimum uplift suggesting that the impacts were oblique rather than vertical An oblique blow would be expected to impart bilateral rather than radial symmetry to resulting *structures* although the *craters* which result from up and outwardly directed explosions should approach more nearly radial symmetry Long after these craters had been destroyed by erosion the underlying formations might be preserved

If the above statements be granted, the problem may be summarized by two questions and their answers Are there any known structures on earth which fulfil the entire list of requirements just described? Can it be proved that those structures have a meteoritic origin? The answer to the first is, Yes' , the answer to the second is 'No or, perhaps Not yet

Distributed widely over the world but not yet adequately studied except in scattered instances are large disturbed regions of the earth's crust known as cryptovolcanic structures They are subcircular, complex domical structures characterized by intense deformation and brecciation within an area of a few square miles Bucher (61) has cited the following characteristics common to six American objects he believes to be cryptovolcanic The same list applies equally well to similar objects anywhere on earth

1 They show a tendency toward a circular outline

2 A central uplift is surrounded by a ring shaped depression with or without well developed marginal folds beyond it.

3 In the larger disturbances the area of the uplifted central part is small compared to the area that sank.

4 Where the nature of the rock materials permits any judgment evidence is found of violent action such as seems explicable only as the result of a sudden release of pressure—that is of explosive force

5 Except in the Decaturville structure no volcanic materials or any signs of thermal action have been observed

It may be mentioned that Tarr (61) has maintained that the igneous rocks in the Decaturville structure are much older than the explosion which was the cause of the structure

At the present time these cryptovolcanic structures are generally believed to have been formed by disturbances produced by the explosive release of gases under high tension, without the extrusion of any magmatic materials, at points where there had previously been no volcanic activity

The known cryptovolcanic structures did not all occur simultaneously or even close together in time They range from early Paleozoic to late Tertiary a ratio of perhaps 50 1 in age It has been pointed out that the cryptovolcanic structures are all found in areas where bedrock layers are well exposed unaffected by intense folding and which have been subjected to close geologic scrutiny How many more lie under the immediate surface hidden by layers of rock and soil deposited subsequently? What

numbers of cryptovolcanic structures have been forever destroyed by the implacable forces of erosion or have been rendered unrecognizable by the processes of folding and mountain building? How many lie waiting on the surface for future geologists to discover?

The features of the various objects are essentially similar, the main differences being the variations in size and the depths to which they have been eroded A brief description of representative objects follows

WELLS CREEK BASIN STRUCTURE (61) TENNESSEE

Aside from the normal faulting this structure reveals more clearly than others the dominant pattern of a cryptovolcanic structure It has the appearance of damped waves a central uplift pushed up at least 1,000 feet surrounded by two pairs of up-and-down folds with diminishing amplitude The inner ring syncline 2¼ miles from the center was dropped at least 300 feet A pattern of this type usually arises from a sudden impulse such as that of an explosion A similar structure is seen on high-speed pictures of a drop of liquid falling into water There are two main differences however The cryptovolcanic formation became frozen in the disturbed position and instead of radial symmetry it exhibits a distinct bilateral symmetry Bucher s interpretation was that a subterranean explosion caused the uplift and that the subsidence was secondary This is diametrically opposed to the suggested meteoritic origin, but it too postulates a violent explosion without any associated features of normal vulcanism

FLYNN CREEK STRUCTURE (62) NEAR GAINSBORO TENNESSEE

A gigantic explosion occurred here in early Kinderhook or late Devonian times when a vast nearly circular crater 2 miles across, was formed Miraculously much of this crater still exists although it scarcely appears as a crater on cursory examination for it has been filled with sediments from the Chattanooga Sea (Mississippian)

In general the major structural features consist of a circular uplift which has raised a small central mass of limestone blocks a vertical distance of approximately 500 feet Surrounding the uplift is a depressed ring of breccia containing blocks from all rock layers included in the disturbance The top layers 12 feet thick are a bedded breccia with layers paralleling the covering Chattanooga shale which later filled the crater These layers probably originated in a fresh water lake occupying the depression in the pre-Chattanooga interval The thickness of the shatter or talus

breccia underlying the bedded breccia is unknown but is probably of the order of 50 feet

In the outer portions of this ring syncline the less disrupted blocks of the Ordovician rocks join with the strata of their respective layers *in situ* On the eastern northern and western flanks of the structure the strata dip at varying angles away from the central uplift On the southern side the strata dip in toward the center, i e , are overturned This latter atti tude is explained as the result of thrusting out from the center

The entire crater was at least 300–350 feet deep relative to the surround ing plain according to the contour map of Wilson and Born (62) This figure probably may be increased to 400 feet when the inflow which forms the brecciated layers is eliminated

At the time of the explosion a great volume of limestone blocks was blown out of the crater some falling back into the pit and the majority being scattered around the margin of the crater within a radius of several miles Since this rim was completely removed by erosion and yet the pit was not filled with air borne sediments the explosion is dated as shortly before the deposition of the Chattanooga shale, or in late Devonian time

Wilson and Born report the important discovery that there is a powder breccia, injected dikelike along fractures in the large blocks of limestone in the central part of the area Stringers or veins of this breccia which range in width from a feather edge to a foot, extend across the blocks In some cases the injection of this rock flour into minor fissures took place on a microscopic scale

A well-developed magnetic high centers about 4 miles south-southwest of the disturbed area. This magnetic high could equally well be the sur face expression of the postulated buried plug of igneous material respon sible for the Flynn Creek disturbance in the cryptovolcanic mode of origin or the effect of buried meteoritic material The offset of 4 miles is the re sult of the high angle dip to the north of the magnetic lines of force in the earth s surface No evidences of volcanic materials have ever been found

SIERRA MADERA DOME (61), TEXAS

Twenty five miles south of Fort Stockton Texas is a large dome which forcibly suggests a cryptovolcanic scar from which the crater and other top layers have been so completely removed by erosion that the under lying structures are revealed According to King (63), this dome is roughly

circular and perhaps 3 miles in diameter It is composed of abruptly up-domed Permian strata which stand nearly vertically or dip radially outward at high angles On the south these beds are overturned and incline toward the center of the dome at angles of 60°–70° The central portions are composed of an unmetamorphosed dolomitic limestone but these regions are highly fractured jointed, and apparently 'jumbled and twisted in hopeless disorder The dome has been drilled (119) to a depth of over 2 miles (12,096 feet) without revealing the presence of an igneous core In fact the structure appears to die out with increasing depth which emphasizes its nonvolcanic origin

Numerous radial tear faults displace the rocks in the center while small folds flank the uplift to the east and west Apparently these are portions of nearly circular damped waves similar to those which appeared so strongly at the Wells Creek Basin Structure On the eastern flank layers of Cretaceous rock lie unconformably on the Permian strata of the structure thereby dating the explosion as post Permian and pre-Comanchean

It is well to realize that while this is the only method capable of dating these cryptovolcanic structures the great discontinuities in geologic history as shown by the rock layers at any particular point leave tremendous spans of time unaccounted for Hence the dates of formation of these objects are uncertain usually by tens of millions of years and often by hundreds of millions

VREDEFORT DOME (64) ORANGE FREE STATE

On a far larger scale the Sierra Madera dome is reproduced in the Vredefort dome in the northern part of the Orange Free State in Africa There is found an almost circular uplift approximately 75 miles across It has a core one-third as wide composed of nonintrusive granite The dome is thus strictly comparable in size to many of the larger of the lunar craters indeed it is wider than Copernicus and approaches Ptolemaeus in diameter Younger rocks which encircle the core are usually overturned so as to dip toward the center of the dome Elsewhere they dip radially outward at high angles

In the Vredefort memoir by Hall and Molengraaff (64) it was suggested that the updoming (not a rebound) was initiated by centripetal pressure The relief of load resulting from this movement caused a younger magma below the granite to become active and to rise and thus assist the updom

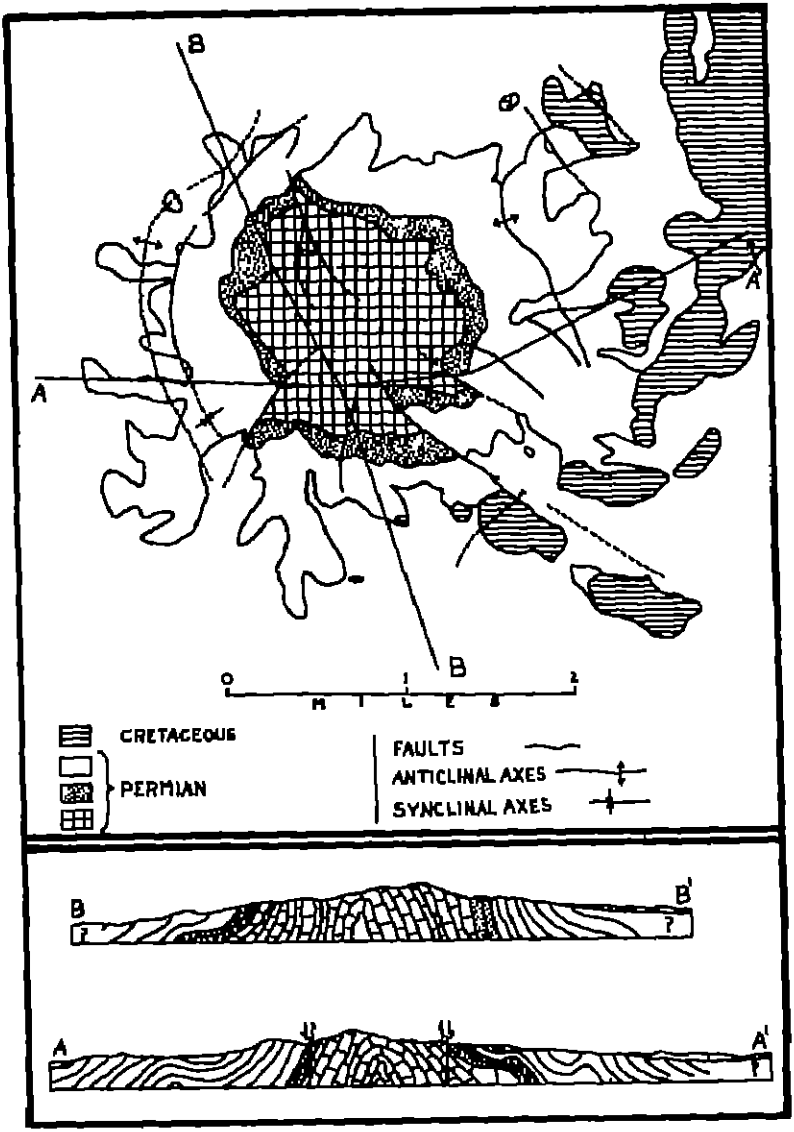


FIG 9 —Map and structure sections of Sierra Madera Dome, Tex (Simplified and redrawn from *U Tex Bull 3038* p 123 Fig 42, 1930)

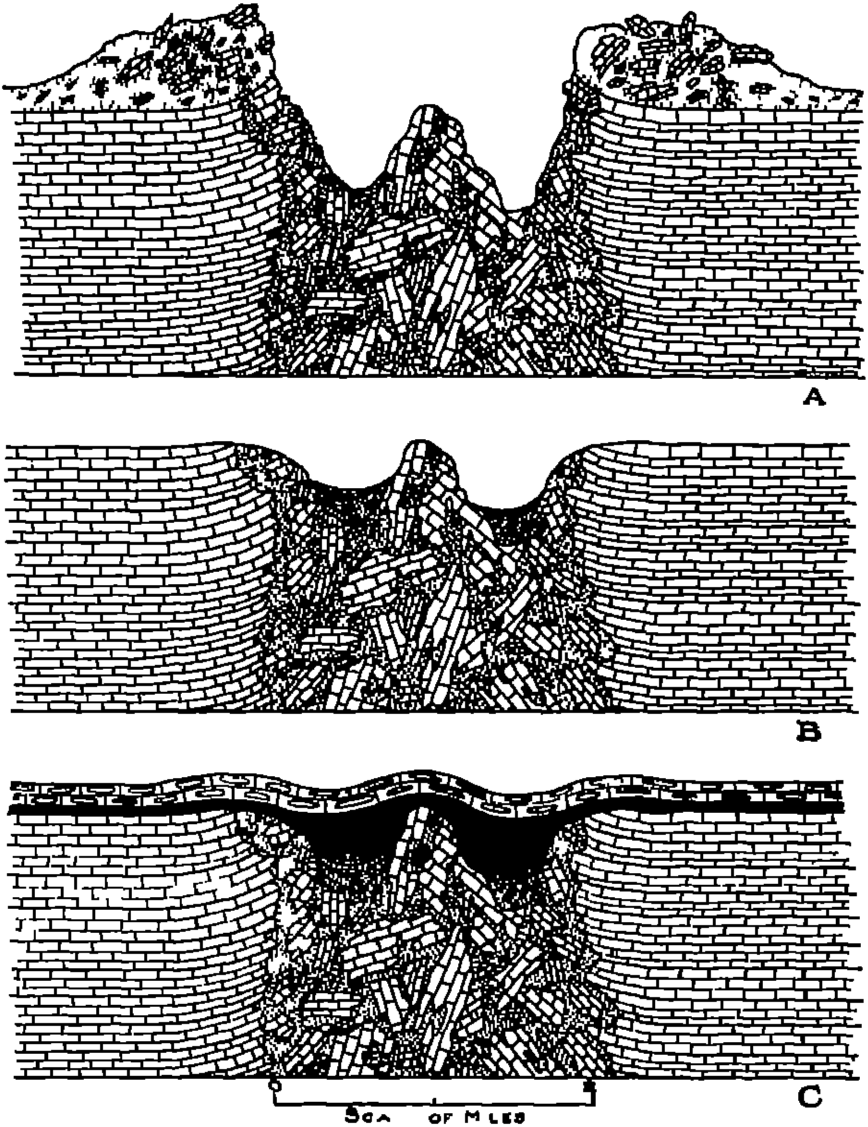


FIG. 10.—Diagrammatic restorations of a section across the Flynn Creek disturbance. *A*, shortly after the explosion; *B*, after erosion had removed all fragmental debris from the vicinity of the crater and after the deepest parts of the crater had been filled in with debris and fresh water deposits; *C*, much later, after the deposition of shale and chert layers. (Wilson and Born [62].)

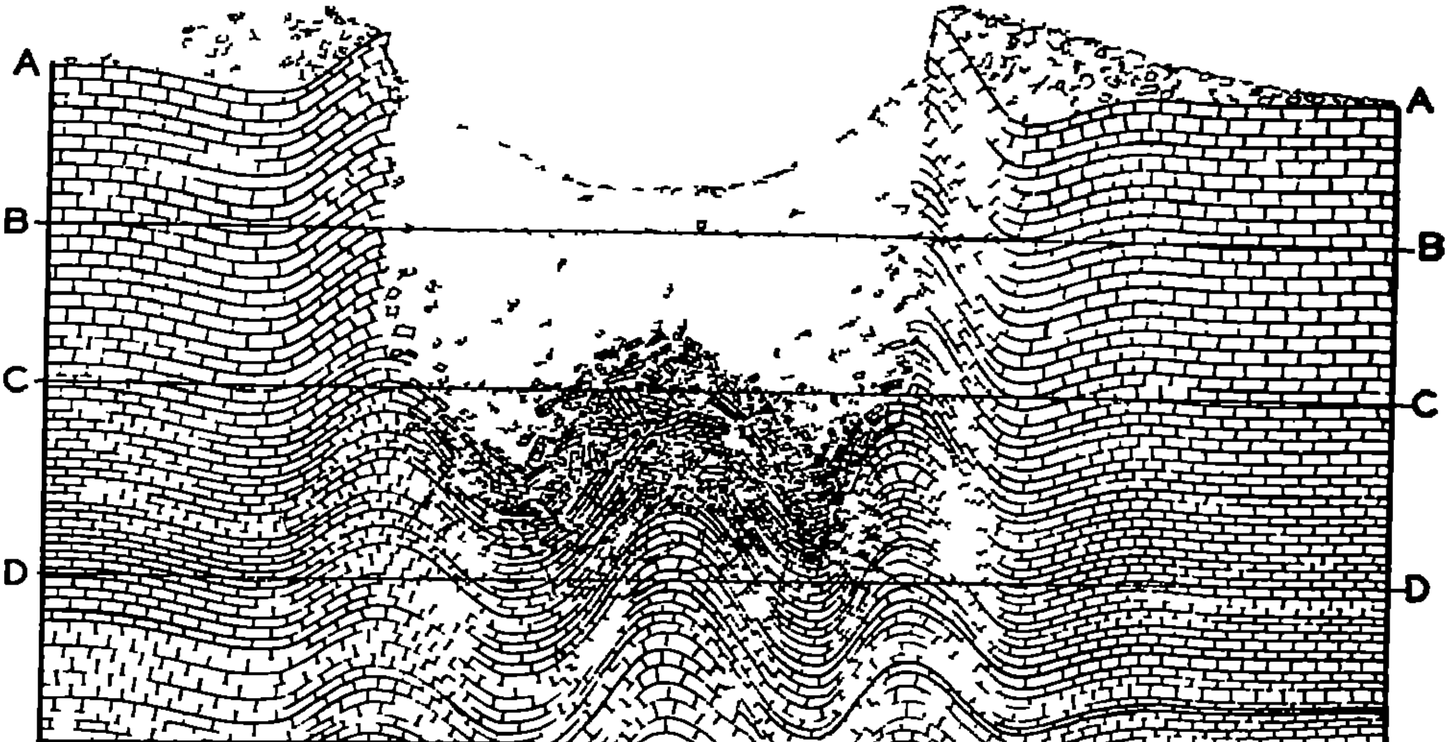


FIG 11 —Attempt by Boon and Albritton to diagram the probable structure beneath a typical meteoritic crater (*Field and Lab.*, 6 44)

ing and the upward movement of the much heated, but passive granite They proposed no motivating cause for the development of the centripetal pressure and emphasized the inadequacies of all existing theories other than the meteoritic by mentioning the extreme difficulty of accounting for an almost circular dome by appealing to tangential stresses

The similarity between this and other cryptovolcanic structures is still further brought out by the presence of transverse and oblique faults around the margins of the core, much like those at the Sierra Madera dome In addition no volcanic materials directly associated with the dome have been identified

Throughout the entire mass of the dome are evidences of unprecedented pressures All the rocks, including the Vredefort granite, reveal under the microscope the effects of these powerful forces They have been crushed and pulverized in many places Evidence for the operation of these pressures appears principally in veins of flinty crush rock which literally riddle the granite and adjoining rocks The volume of the crushed and shattered materials has been estimated as high as 800 000,000 cubic meters [2]

THE STEINHEIM BASIN (61) GERMANY

In 1905 Branca and Fraas (65) coined the term *Kryptovulcanic* since anglicized to cryptovolcanic for the Steinheim Basin in southern Germany This depression commences abruptly in a plain of flat Jurassic limestone At present it measures about 1½ miles in diameter and is roughly 260 feet deep Whatever rim it once had has been removed by erosion. In the center is a gently rounded hill the Klosterberg 120 feet high composed of older Jurassic rocks than the other parts of the basin Obviously the Klosterberg is the remnant of a domical structure from which the younger rocks have been stripped The basin proper is either the remains of a meteoritic crater itself, with its accompanying central peak or else is the downthrow of a ring syncline such as is usually found as an integral part of the lower layers of a cryptovolcanic structure

The evidence points strongly to the crater explanation The original pit, formed in Miocene times was filled with a Miocene lake without drainage exits Hence even early in its history the Steinheim Basin was a surface formation

2 R A Daly is another prominent scientist who has given the meteoritic impact theory of the origin of this peculiar structure some backing (123)

Today the rim has been twice breached, so the lake has been converted into placid farm land. It seems probable that the net effects of erosion have simply been to reduce the initial 500-foot uplift of the Klosterberg and to remove the raised rim, meanwhile depositing sediments in the crater.

Several other factors lead to the same conclusions. No volcanic materials are present at Steinheim. The only extraneous objects are occasional large blocks of the usual Jurassic limestone which obviously had been hurled from the pit at its formation.

The region of activity is sharply bounded by a rough circle. Inside this limit the explosive forces operated with tremendous effects. Outside, apparently nothing was changed.

Rohleder says that "there is nothing whatever to prove the volcanic origin of the Steinheim Basin and the fact that the immediate neighborhood was in no way involved seems to point out that whatever caused the basin was an absolutely local event" (66), i.e., a meteorite.

The meteoritic origin of the Steinheim Basin has not been proved. However, the usual volcanic processes certainly did not operate; and, while the cryptovolcanic nature of the structure has been questioned, it may well be that the Steinheim Basin is the surface expression of a true cryptovolcanic structure. The nearest parallel is the Flynn Creek Structure.

THE RIESKESSEL (61), GERMANY

Not far from the Steinheim Basin is another great depression, the Rieskessel, whose floor measures 13 by 15 miles across and consists of a chaotic jumble of broken granite, Triassic and Jurassic sediments, beneath a cover of Upper Miocene fresh-water deposits.

Williams (23), after rejecting the meteoritic theory of its origin without stating his reasons, described the Rieskessel as follows, implying a volcanic origin, but continually emphasizing the complete inadequacies of the known terrestrial processes:

> Immediately surrounding the basin is a zone, several miles wide, made up of similar fragmented rocks in the form of large blocks and huge, imbricated thrust slices. This is the so-called *Schollen- und Schuppen-Zone*. Beyond this and resting on the undisturbed limestones of the Alb Plateau, are rootless slices and smaller blocks of older rocks, thrust outward from the central area (Zone der wurzellosen Schollen). Still

farther from the basin are scattered pieces of limestone some of which even 44 miles from the center of the Ries measure 40 cm across

How are these peripheral zones of ejected blocks and thrust masses to be explained? Most authorities agree that during Miocene times the crystalline crust and its Mesozoic cover were strongly uparched perhaps more than 400 meters by the intrusion of a broad laccolith Geophysical studies suggest that the laccolith is composed of basic rock and lies at a depth of only a few kilometers Possibly the central portion of the upraised area was punched up in bysmalithic fashion so that rocks formerly well below the surface were exposed In any event, a steep doming of the laccolithic roof seems to have brought about widespread sliding on the surface and this process was undoubtedly accentuated by repeated explosions With good reason Reck doubts that the larger slices in the *Schollen- und Schuppen Zone* could have been blown out. No masses even approaching them in size have ever been ejected in the most violent of historic eruptions Had these huge slices of brittle limestone been hurled out by explosion why were they not shattered as they fell and why do they commonly show slickensides on their under surfaces? These features suggest that they were emplaced by sliding It cannot be denied that much of the finer debris surrounding the Ries is truly pyroclastic but Kranz s [67] view that the depression is a colossal explosion crater does not seem justified True torsion balance measurements have indicated a funnel shaped structure approximately 12 km in diameter from 0 9 to 1 3 km deep and with sides sloping inward at 10° to 15° beneath the center of the caldera but that this is a gigantic explosion vent has yet to be proved No known explosion craters exceed even a quarter of this in diameter To produce a broadly flaring funnel of so great proportions it is obvious that the explosion focus must be very shallow But at shallow depths magma can hold little gas in solution and can only produce explosions of weak to moderate intensity such as would puncture the roof by a series of diatremes. No new magma was associated with the first explosions of the Ries they seem to have been low temperature phreatic eruptions All the more is there reason for doubting the theory of Kranz.

Bentz Branca Reck and others agree that after the main explosive phase the summit of the dome collapsed along ring fractures and that it was primarily this engulfment which formed the caldera Rittmann also seems to adopt this view when he refers to the Rieskessel as a volcano-tectonic sink. After the collapse dikes of suevite were injected close to the margins of the basin and mild explosions of suevite pumice ensued Apparently the magma was produced by gas fluxing of the granitic basement

Certain observations are pertinent An uparching of 400 meters in a radius approximating 10 kilometers gives an average slope of 1 in 25 roughly 2 Great masses certainly would not slide on such a slope hence the overthrust masses must have been emplaced by an explosion or explosions acting nearly horizontally This effect in minor form is well known at the small modern terrestrial meteoritic craters (see Fig 8) Williams objection to the explosion hypothesis seems to be based entirely on the fact that no volcanic explosion of such a magnitude is known to have oc

curred anywhere on earth. The meteoritic impact theory avoids these difficulties completely, for ample energy is available.

The incidence of a mild form of vulcanism, the injection of suevite in ring dikes, is not surprising. An explosion of the obvious magnitude of this one might easily weaken the crustal layers, particularly in a volcanic area, whereas smaller explosions probably would not.

The best known cryptovolcanic structures are included in Table 2.

TABLE 2

CRYPTOVOLCANIC STRUCTURES

Name and Location	Approximate Plan of Disturbed Area	Approximate Diameter (Miles)	Date of Formation
Jeptha Knob, Ky	Circular	2	Mid-Silurian
Serpent Mound, Ohio	Circular	4	Post Lower Mississippian pre-Illinoian
Wells Creek, Tenn	Circular	6	Post Middle Mississippian
Decaturville, Mo.	? Concealed	?	Late Cambrian or early Ordovician
Kentland, Ind.	? Concealed	?	Post Middle Ordovician pre-Pleistocene
Flynn Creek, Tenn	Circular	2	Late Devonian or early Mississippian
Upheaval Dome, Utah	Circular	3	Post Navajo (Jurassic)
Sierra Madera, Tex.	Circular	3	Post-Permian pre-Comanchean (Cretaceous)
Howell, Tenn.	Circular	1	Ordovician
Vredefort Dome, Orange Free State	Circular	75	Pre-Carboniferous
Steinheim Basin, Germany	Circular	1½	Miocene
Rieskessel, Germany	Circular	15	Miocene

Only at the Flynn Creek, Howell, Steinheim Basin, and the Rieskessel are there remnants of the crater remaining. Of the above list, the Jeptha Knob, Serpent Mound, Wells Creek, Flynn Creek, and Sierra Madera structures show pronounced bilateral symmetry. This proportion of those which show bilateral rather than radial symmetry is about what would be expected if the cryptovolcanic structures were actually produced by meteoritic impact. The majority of meteorites would strike the earth at angles other than the vertical, and, although the resultant surface craters probably would be very similar to those formed by impacts of bodies falling perpendicularly, the subjacent rocks would indicate both the fact that an angular fall had occurred and its direction. Dietz (117) noticed that what

ter cones" at the Kentland structure are oriented with their apexes toward the top of the beds, suggesting that the compressive force came from above.

On the other hand, it seems to be extremely difficult to explain these cryptovolcanic formations as the results of stresses originating in the earth's crust. Most writers opposing the meteoritic theory lean toward one of two ideas: first, that there had developed terrifically compressed pockets of gas close below the surface and that, when the pressure had reached a sufficient value, the top blew off and a crater was produced along with the rebound formation, which then remains as a rock dome.

Two objections may be placed against this theory. The gas pressure must have developed near the surface, close to the depth of the base of the crater. From all that we know regarding the strengths of rock layers this is impossible. The materials simply are not strong enough to permit such an accumulation of gas at small depths. In addition, the maximum gas pressure on the subjacent rocks would have occurred at the instant of explosion. The blast would have relieved the pressure locally, mainly according to the amount of matter ejected in forming the pit. A rebound would have been out of the question; an upthrust initiated by deeper gas or magma upon the release of load could have produced a dome, but it appears that the magnitude of the doming effort is out of proportion to the reduction in crustal load.

The usual alternative explanation of the cryptovolcanic structures is that the gas pressure developed deep below the surface. The strength-of-materials argument does not hold here, but if the explosion were deep-seated, producing a domical structure, it is difficult to see how a surface crater could have developed, for in none of these objects is there a recognized neck or channel by which the expanding gases could escape to the surface. If the explosion were deep-seated, then the crater could have originated only if the ascending shock wave were powerful enough to knock some of the ground layers into the air much as a stone striking a windshield will often cause a funnel-shaped chip to fly off the other side.

To avoid some of these difficulties, certain attempted geologic explanations have postulated two explosions, one directly over the other. The odds are definitely against this, even without the corroborating evidence that the Sierra Madera dome fades out with increasing depth. The explo-

sion focuses for these peculiar objects were shallow, not far below the surface.

Under any assumptions one or more explosions must be considered to have happened. It seems strange that these cryptovolcanic structures range down to 1 or 2 miles in diameter when all the truly explosive volcanic craters now known, as contrasted to the collapse caldera, are 2 miles or less in diameter. If both types of formation were caused by the release of subterranean gas pressure, their basic causes were far different. This is strikingly brought out by the lack of volcanic materials associated with the cryptovolcanic structures, the ones which were born during the more violent spasms.

Perhaps the chief objection to any deep-seated cryptovolcanic explosion theory is that it cannot account for the upraised and overtilted rim rock layers. Hack (68) in his study of the ordinary volcanic craters in Arizona was not able to find any deformation of the bedrock in the rims of the many volcanoes which he investigated.

The meteoritic-impact theory thus seems to fit the observed facts better than any other. It alone explains the bilateral symmetry so often found, and it alone seems capable of supplying the vast amounts of energy which are needed to give the observed results.

Only one of two factors is now needed completely to establish the impact theory. The mass of the meteorite itself, in producing one of these vast objects, would probably be largely blasted back out of the crater and scattered over the surrounding landscape where erosion would soon remove it. However, it is possible that some microscopic fragments of nickel iron would remain, even to this day, imbedded in the rock of some of the less eroded structures, such as that at Flynn Creek. If meteoritic iron is ever discovered associated with cryptovolcanic structures, then one of the greatest riddles in geologic history will have been solved.

The other demonstration of the origin of such a structure would be for one to be formed today. The chances against such an occurrence soon are perhaps millions to one, but the possibility exists, as witness the numbers of small asteroids which in the past few years have passed within a very few hundreds of thousands of miles of the earth. If one of them ever collided with the earth, the effect would be far worse than any battlefield holocaust, atomic bomb or otherwise; but after the immediate personal

effects wore off, it would answer many questions regarding the past history of the earth and moon

In spite of all the favoring evidence, it is possible that few or none of these cryptovolcanic structures had a meteoritic origin If so another mode of genesis must be found to account for them, and the scientist must look farther afield for the fossil meteorite scars which must exist It cannot be conceived that the Arizona meteorite crater and others like those at Odessa Texas which are all modern represent the accumulations of the ages

Written in the Book of Geology in still obscure characters are the records of hundreds of thousands of collisions of the earth and extra terrestrial bodies

CHAPTER 6

Relationships

OF ABSOLUTELY fundamental importance in establishing the mode of crater genesis is the necessity for determining whether or not there exist relationships and similarities between the lunar craters of all sizes and in all conditions. If no correlations are to be found between the different crater dimensions or if they are very weak, the necessary conclusion is that the lunar craters originated as physical expressions of perhaps similar but random forces, each pit taking its position and contour from purely local conditions. If definite relationships are found, one may reasonably expect that these structures were each formed by variant applications of the same forces. A high degree of correlation means a smooth transition from craters of a given size to those immediately larger and smaller with only slight changes in both relative and absolute dimensions.

In order to interpret such statistical relationships as may exist, it is necessary to tie them into terrestrial functions of established character.

In the early days, when the moon was not a subject anathema to many astronomers because of its interference with other delicate observations, men laboriously charted and studied the lunar surface. They did not have the advantages of modern instruments or photographic equipment and technique, but they did have the qualities of patience and perseverance and thus managed to accumulate much valuable information. Schröter (69), working with his tiny telescope and "projection machine,"[1] made all sorts of measurements of the craters. He measured their diameters, depths, slopes of walls, both inner and outer, and determined the height of the piled-up rim material above the surrounding moonscape—all this for a great many of the craters, large and small. Eventually his care was rewarded in the establishment of a new general relationship, one which to this day is known as Schröter's Rule: "For each crater the part of the ma-

1. A white screen divided into half-inch squares carried by a bar at right angles to the telescope, at a distance generally of 32½ inches, giving a scale of 20″ to the half-inch; and it was used by projecting the image seen by one eye onto the screen viewed with the other.

terial above the surface is approximately equal to the volume of the interior depression below the surface'

MacDonald (70) and Ebert (71) have re-examined the problem and have found an essential agreement with Schröter's early work No one has claimed that this rule is a universal truth Certain craters are known in which the volume of the rim material would not fill the depression Others may be found which exhibit a reverse condition Nevertheless the tremendous numbers of craters which do fulfil the requirements of Schröter's Rule point strongly to the conclusion that the matter contained in the raised rims is actually shattered rock which was formerly crustal material violently displaced by the forces which produced the craterpit In this view the lunar craters were born in cataclysmic explosions originating not far beneath the surface No choice can be made here between the single or multiple-explosion theory

Implicit in Schröter's Rule is another fact recognized even earlier namely that the lunar crater is a great pit, deep in the absolute sense shallow relatively Its floor except in certain cases where there are other obvious explanations is sunken, usually several thousands of feet Here is the greatest possible contrast to a terrestrial volcano Here is no volcanic neck funneling magmatic materials from basement reservoirs to the surface where they accumulate into a vast graceful mountain with a relatively tiny craterpit high in the peak Here is a new type of object a structure scarcely known on the earth a formation whose development if volcanic in nature must be vulcanism of a sort completely unknown to modern geology

The next great step forward was made by Ebert (71) He first showed conclusively that the lunar craters belonged to one family and that there was a progressive change in form with increasing diameter For the smaller pits ranging up to perhaps 20 miles in diameter the depths scattered around an approximate value equal to 10 per cent of the width As the size increased the absolute depth increased, but not as rapidly as the diameter The lunar craters thus become relatively more shallow as they grow broader At 60 miles the depth is possibly 5 per cent of the diameter and it may be 2 5-3 0 per cent for the largest craters

The establishment of the true values of diameter or depth for craters on the moon is of academic interest The correlating of these facts leading to the expression of such a rule is of fundamental importance From Ebert's

Rule we must conclude that the craters originated in similar applications of one basic force and that an overwhelming majority of all lunar craters were formed in this manner.

To find that there exists a clear-cut relationship between the diameter and depth of the craters on the moon which is valid over a range of diameters differing by at least a factor of 30 is tantamount to determining that one process and one process only was responsible for the birth of essentially all these structures. This is not to be taken as denying the existence of crater like or crater related forms on the moon which originated in entirely different manners, but it does relegate such processes to an extremely secondary role.

Fauth (72) has attacked the problem from another direction. From measures on 162 craters he determined that the mean slope of the inner

TABLE 3

RELATIONSHIP BETWEEN DIAMETER AND INNER SLOPE (FAUTH)

Diameter (Km.)	Average Diameter (Km.)	N	Mean Inner Slope
0– 30	12	113	33.5
30– 50	38	14	22.7
50–100	76	27	14.8
100+	144	8	11.6

wall was directly related to the diameter in the sense that, the greater the diameter the lesser is the inner slope.

Fauth's work merely corroborates that done by Ebert. Both sets of data illustrate the progressive change in depth of lunar craters as a function of diameter. Below 30 km. he found no significant change.

With respect to the slopes of the outer walls of the craters an equal unanimity is apparent. MacDonald (70) states that his measures indicate far more gradual slopes than inside the pits. Values of 1°–3° are standard. Schmidt (8) found 3°–8° although Neison (7) quotes Schmidt as finding slopes of 1°–4°. Neison's own figures showed a range from 1° to 3° near the foot, the portion of the slope joining the external plain, and from 2° to 6° toward the summit.

These values are strangely revealing. They clearly show that the crater rims all belong to one family, but even more important is the fact that in

no case is the external slope even of the same order of magnitude as the angle of repose for solid particles On the earth the angle of repose for fine volcanic ash is about 30°–35° This increases to 40°–45° for coarser scoria and slag masses It may confidently be expected that these values are somewhat larger on the moon with its reduced surface gravity

For liquid materials the viscosity determines the angle of repose In Hawaii and Iceland the lavas (basalt) were of great fluidity They spread great distances and their slopes rarely exceed 8°

Several possibilities suggest themselves The outer walls might have been formed by the cooling of lavas. The slopes are of the correct order of magnitude for this hypothesis These rims might have been domed up from the flat surface by subselenian forces They certainly were not deposited as volcanic ash and scoria but they could have been formed by the nearly horizontal ejection of matter from a central explosion The choice of solution here must of necessity be made in conjunction with the interpretation of the origin of the main excavation

The smallest craters on the moon on which measurements have been made are 1 mile in diameter More or less accurate figures are known for 329 lunar craters These data are listed in Table 4 Most of the measurements were made by Schmidt (8) some by Beer and Mädler (19) and a few by Neison (7) MacDonald s (70) tabulation of earlier measures was drawn upon substantially Data on 29 of the smallest craters were derived by the author An idea of the accuracy of the determinations of heights and depths may be realized from an analysis of Schmidt s measures made at different limb distances and under different librations The probable error of the best determinations is roughly 150 feet it may be 1 000 feet for poorer values

MacDonald (70) has drawn some interesting conclusions from the data in his list In this work he divided the craters into two main types—normal craters and walled plains The distinction between these two types is somewhat uncertain but is based primarily on the extent of the relatively flat floor of the pit and on the presence or absence of a marked central peak MacDonald found apparently a real difference between the two forms in that the walled plains averaged relatively more shallow than the normal craters However still another conclusion seemed to be forced by his data It is obvious of course that the moon s visible surface is divided into two roughly equal parts There are extensive gray areas old lava

TABLE 4

Lunar Crater Data

Name	Class	Diameter (Miles)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Central Peak
Clavius	2	146	5 89	16 100	4 21	5 400	3 73	M*
†	4a‡	139	5 87	(5 000)§	(3 70)			
Grimaldi	4	137	5 86	8 700	3 94			
Schickard	4	134	5 85	8 500	3 93	(6 400)	(3 81)	
W Humboldt	2	130	5 84	14 000	4 15			M
Maginus	3	118	5 79	14 800	4 17			M
Schiller‖	3	112	5 77	13 000	4 11	(9 000)	(3 95)	X
Petavius	4	105	5 74	8 000	3 90			M
Riccioli	3	99	5 72	(11 200)	(4 05)			?
Hipparchus	4	93	5 69	(6 900)	(3 84)			M
Ptolemaeus	4	90	5 68	4 000	3 60	(8 200)	(3 91)	
Longomontanus	2	90	5 68	14 800	4 17	(6 100)	(3 79)	M
Stoflerus	2	90	5 68	12 300	4 09	(4 800)	(3 68)	
Newton ¶	1	85	5 65	20 000	4 30			1
Walter	4a	85	5 65	9 800	3 99	(6 700)	(3 83)	M
Vendelinus	4	84	5 65	8 400	3 92	(4 900)	(3 69)	
Furnerius	3	81	5 63	10 000	4 00			
Hommel	3	81	5 63	(11 000)	(4 04)			1
Langrenus	1	81	5 63	13 300	4 12	2 600	3 41	M
Albategnius	4	80	5 63	9 400	3 97			M
Cleomedes	4	80	5 63	9 700	3 99	(5 200)	(3 72)	M
Pythagoras	1	80	5 63	16 100	4 21			M
Endymion	4	78	5 61	8 400	3 92			
Moretus	1	77	5 61	14 600	4 16			M
Purbach	4	75	5 60	7 400	3 87			M
Neper	4	75	5 60	6 000	3 78			1
Alphonsus	4	75	5 60	6 400	3 81			M
Hevel	4	71	5 57	6 000	3 78			1
Maurolycus	2	71	5 57	14 300	4 16			M
Phocylides	3	71	5 57	7 700	3 89	(6 600)	(3 82)	
Blancanus	1	70	5 57	12 000	4 08			M
Scheiner	2	70	5 57	14 600	4 16			
Letronne	4	68	5 56	3 300	3 52			M
Catherina	4a	66	5 54	9 000	3 95			M
Boguslawski	2	65	5 54	11 200	4 05			
Anaximines	4	65	5 54	8 000	3 90			
Theophilus	1	65	5 54	14 400	4 16	3 800	3 58	M
Arzachel	3	62	5 51	10 800	4 03	(5 900)	(3 77)	1
Posidonius	4	62	5 51	6 700	3 83	3 300	3 52	
Inghirami	2	60	5 50	12 000	4 08			?
Pontecoulant	4	60	5 50	6 000	3 78			
Fracastorius	4	60	5 50	7 700	3 89			
Manzinus	1	60	5 50	12 500	4 10			
Plato	4	60	5 50	7 900	3 90			
Wilhelm I	3	60	5 50	10 000	4 00			M
Copernicus	1	56	5 47	11 000	4 04	3 300	3 52	M
Piccolomini	1	56	5 47	12 100	4 08	(3 900)	(3 59)	M
Vlacq	1	56	5 47	10 700	4 03			M
Aristoteles	1	56	5 47	10 000	4 00	(3 600)	(3 56)	M

* M in the Central Peak column signifies central levation with two or more peaks. The n mber 1 means that there is only one recognized peak The height of the central elevation is not considered in this table Only its presence absence is noted. X signifies that because this crater is composit the presence or bsence of central peak cannot be determined definitely

† Nameless. Great ruined closure east of Walte

‡ Craters in Class 4a are very ancient but may not be l va filled.

§ A parenthesis denotes an uncertain value

‖ Schille is composed of at least four overlapping craters

¶ Newton is usually described as an elongated crater 140 by 65 miles. From measurements on photographs it appears to be mu h more nearly circular with an average diameter of 85 miles.

TABLE 4—*Continued*

Name	Class	Diameter (Miles)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Central Peak
Orontius	3	56	5 47	(10 200)	(4 01)	(5 900)	(3 77)	
Sacrobosco	3	56	5 47	12 000	4 08			?
Cyrillus	3	55	5 46	11 600	4 06	4 800	3 68	M
Gassendi	4	55	5 46	6 600	3 82			M
Hainzel	2	55	5 46	11 800	4 07	(5 200)	(3 72)	M
Tycho	1	54	5 45	12 000	4 08	7 900	3 90	1
Wargentin	4	54	5 45	200	2 30			
Atlas	4	53	5 45	7 700	3 89	4 300	3 63	M
Geminus	1	53	5 45	11 800	4 07	3 900	3 59	1
Gemma Frisius	3	53	5 45	15 300	4 18			M
Aliacensis	1	53	5 45	13 100	4 12			1
Pitiscus	2	52	5 44	10 200	4 01			1
Snellius	1	51	5 43	9 700	3 99			1
Vieta	2	51	5 43	11 300	4 05			1
Barocius	2	51	5 43	11 800	4 07	10 500	4 02	M
Mutus	2	51	5 43	11 800	4 07			
Anaximander	4	50	5 42	5 900	3 77			
Archimedes	4	50	5 42	6 100	3 79	4 800	3 68	
Cuvier	1	50	5 42	10 200	4 01	(3 400)	(3 53)	
Bettinus	1	50	5 42	12 500	4 10			1
Berosus	1	50	5 42	11 800	4 07			
Metius	2	50	5 42	10 200	4 01	(5 700)	(3 76)	M
Fabricius	2	50	5 42	11 500	4 06			M
Pentland	1	50	5 42	12 100	4 08			M
Schomberger	1	50	5 42	14 900	4 17			M
Licetus	1	48	5 40	11 600	4 06	(4 900)	(3 69)	1
Rosenberger	3	48	5 40	(7 100)	(3 85)			M
Wurzelbauer	4	47	5 39	(5 600)	(3 75)			M
Colombo	4	47	5 39	7 200	3 86			M
Stevinus	1	47	5 39	10 200	4 01	(5 600)	(3 75)	1
Philolaus	1	46	5 39	9 700	3 99			M
Zach	2	46	5 39	11 300	4 05			1
Legendre	3	46	5 39	(7 700)	(3 89)			1
Condorcet	4	45	5 38	8 500	3 93			
Casatus	2	45	5 38	12 100	4 08	7 400	3 87	M
Eudoxus	1	45	5 38	10 500	4 02	8 200	3 91	M
Byrgius	3	45	5 38	7 000	3 85			
Steinheil A	1	45	5 38	11 000	4 04			
Hercules	1	45	5 38	10 000	4 00			M
Simpelius	1	45	5 38	14 900	4 17			1
Werner	1	45	5 38	14 400	4 16	5 700	3 76	M
Santbech	1	43	5 36	11 200	4 05	(3 600)	(3 56)	M
Clairaut	2	43	5 36	8 900	3 95			?
Stadius	4	42	5 35	130	2 11			
Mersenius	3	42	5 35	7 900	3 90	4 300	3 63	(C) **
Macrobius	1	41	5 33	10 500	4 02	(5 100)	(3 71)	M
Lacaille	3	40	5 32	9 000	3 95			
Bacon	1	40	5 32	10 200	4 01			1
Guttemberg	4	40	5 32	5 700	3 76			M
Nearchus	1	40	5 32	10 800	4 03			
Faraday	2	40	5 32	12 600	4 10	(5 700)	(3 76)	M
Hase	2	40	5 32	7 500	3 88			
Jacobi	2	40	5 32	10 300	4 01	3 600	3 56	
Cavalerius	1	40	5 32	10 200	4 01			1
Rheita	1	40	5 32	10 200	4 01			1
Abulfeda	1	39	5 31	9 500	3 98			
Gruemberger	2	39	5 31	14 400	4 16			M

** The crater Mersenius has convex floor This is an exaggerated case of frequent condition

TABLE 4—*Continued*

Name	Class	Diameter (Miles)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Central Peak
Apianus	2	38	5 30	9 000	3 95			
Firmicus	4	38	5 30	5 000	3 70			
Zuchius	1	38	5 30	10 000	4 00			M
Lilius	1	38	5 30	10 300	4 01			M
Bullialdus	1	37	5 29	10 500	4 02			M
Eratosthenes	1	37	5 29	10 300	4 01	3 300	3 52	M
Kircher	1	37	5 29	(14 100)	(4 15)			
Cassini	4	36	5 28			3 300	3 52	M
Short	1	36	5 28	14 800	4 17			1
Scoresby	1	36	5 28	10 500	4 02	3 600	3 56	M
Taruntius	4	35	5 27	3 800	3 58	2 100	3 32	1
Bayer	1	35	5 27	8 000	3 90			
Burckhardt	1	35	5 27	12 700	4 10			M
Aristillus	1	35	5 27	10 300	4 01	4 400	3 64	M
Franklin	2	35	5 27	7 900	3 90			
Miller	1	35	5 27	10 800	4 03			M
Capuanus	4	35	5 27	6 000	3 78			
Cysatus	1	35	5 27	11 800	4 07			
Heinsius	3	34	5 26	9 700	3 99			
Guericke	4	34	5 26			2 100	3 32	
Pictet	3	34	5 26	9 700	3 99			M
Neander	2	34	5 26	8 200	3 91			1
Le Monnier	4	33	5 24	8 000	3 90			
Fernelius	3	33	5 24	(5 700)	(3 76)			
Almanon	2	32	5 23	6 600	3 82			
Cardanus	2	32	5 23	4 000	3 60			1
Seleucus	1	32	5 23	10 000	4 00			1
Cavendish	3	32	5 23	6 000	3 78			1
Delambre	2	32	5 23	9 800	3 99			1
Plinius	1	32	5 23	(7 400)	(3 87)	2 000	3 30	M
Apollonius	4	31	5 21	5 000	3 70			
Lindenau	1	31	5 21	8 500	3 93			M
Anaxagoras	1	31	5 21	7 700	3 89			1
Vendelinus B	2	31	5 21	(8 400)	(3 92)			
Hansteen	4	31	5 21	3 000	3 48	2 600	3 41	M
Billy	4	31	5 21	3 600	3 56	2 500	3 40	
Campanus	4	30	5 20	5 900	3 77			
Thebit	2	30	5 20	9 200	3 96			M
Segner	3	30	5 20	8 400	3 92	(6 400)	(3 81)	
Azophi	1	30	5 20	10 200	4 01	(3 800)	(3 58)	
Beaumont	4	30	5 20	5 400	3 73	3 000	3 48	
Epigenes	4	30	5 20	5 200	3 72			1
Mercator	4	30	5 20	4 800	3 68			
Clavius b	1	30	5 20	13 100	4 12	8 000	3 90	M
Fourier	2	30	5 20	7 700	3 89			
Nasireddin	1	30	5 20	9 000	3 95			M
Sirsalis	1	30	5 20	(10 200)	(4 01)			1
Wrottesley	1	30	5 20	9 000	3 95			M
Miller A	1	30	5 20	10 000	4 00			1
Frauenhofer	3	30	5 20	5 000	3 70			1
Reinhold	1	29	5 18	9 000	3 95	2 300	3 36	M
Aristarchus	1	29	5 18	6 900	3 84	2 600	3 41	1
Bernoulli	1	29	5 18	9 800	3 99			1
Römer	1	29	5 18	9 500	3 98			1
Vitello	4	29	5 18			4 900	3 69	M
Bacon b or B	1	29	5 18	9 200	3 96			1
Agatharchides	4	29	5 18	3 800	3 58	2 500	3 40	M
Saussure	2	29	5 18	6 200	3 79			
Kies	4	28	5 17			2 000	3 30	

TABLE 4—*Continued*

Name	Class	Diameter (Miles)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Central Peak
Playfair	2	28	5 17	8 200	3 91			
Kaiser	3	28	5 17	(5 700)	(3 76)			?
Busching	3	28	5 17	4 000	3 60			
Landsberg	1	28	5 17	7 700	3 89	3 000	3 48	1
Agrippa	1	27	5 16	7 500	3 88	(3 800)	(3 58)	1
Cepheus	1	27	5 16	9 200	3 96			1
Rothmann	1	27	5 16	8 500	3 93			?
Parry	4	27	5 16	(4 800)	(3 68)	(3 400)	(3 53)	
Isidorus	3	27	5 16	(5 200)	(3 72)			
Marius	4	27	5 16	4 500	3 65			1
Bacon A	1	26	5 14	8 400	3 92	(4 800)	(3 68)	?
Newton a	1	26	5 14	9 400	3 97			?
Bürg	1	26	5 14	6 200	3 79			1
Abenezra	1	26	5 14	10 300	4 01	(3 800)	(3 58)	1
Alpetragius	1	26	5 14	9 000	3 95	3 300	3 52	1
Herschel	1	26	5 14	9 400	3 97			M
Ball	1	25	5 12	5 000	3 70			1
Tacitus	1	25	5 12	11 000	4 04			1
Democritus	1	25	5 12	5 000	3 70			1
Tralles	2	25	5 12	(9 200)	(3 96)			M
Bianchini	1	25	5 12	8 400	3 92			1
Geber	1	25	5 12	8 400	3 92			1
Mairan	1	25	5 12	8 700	3 94	4 300	3 63	
Lilius a	1	25	5 12	10 000	4 00			?
Manilius	1	25	5 12	7 700	3 89	3 000	3 48	M
Mercurius	2	25	5 12	7 500	3 88			1
Stiborius	1	25	5 12	9 400	3 97			1
Taylor	1	25	5 12	7 400	3 87			1
Vendelinus A	1	25	5 12	(6 700)	(3 83)			M
Tisserand	2	25	5 12	9 000	3 95			?
Colombo A	1	25	5 12	8 000	3 90			
Rost	1	25	5 12	7 900	3 90			
Magelhaens	4	25	5 12	4 600	3 66			
Fermat	2	25	5 12	6 000	3 78			
Herodotus	4	24	5 10	4 400	3 64			
Schröter	4	24	5 10			(5 100)	(3 71)	
Harpalus	1	24	5 10	(7 900)	(3 90)	(3 100)	(3 49)	M
Autolycus	1	24	5 10	9 500	3 98	4 800	3 68	1
Reichenbach H	2	24	5 10	(7 400)	(3 87)			1
Sharp	1	24	5 10	9 200	3 96			1
Archytas	1	23	5 08	6 200	3 79			M
Condamine	4	23	5 08	(3 400)	(3 53)			M
Davy	4	23	5 08	(4 400)	(3 64)	3 400	3 53	1
Newton c	1	22	5 06	14 100	4 15			?
Helbig	1	22	5 06	7 700	3 89	5 900	3 77	?
Sömmering	4	22	5 06	(4 800)	(3 68)	(3 400)	(3 53)	M
Barocius b	1	22	5 06	7 400	3 87			1
Wurzelbauer d	1	22	5 06	8 000	3 90			
Egede	4	22	5 06	400	2 60			
Godin	1	22	5 06	7 700	3 89			1
Timocharis	1	22	5 06	7 100	3 85	3 400	3 53	1
Fontenelle	4	22	5 06	6 100	3 79			
Kant	1	22	5 06	7 500	3 88			1
Halley	2	21	5 05	(7 500)	(3 88)	(3 600)	(3 56)	
Kepler	1	21	5 05	7 500	3 88			1
Mason	4	21	5 05	(6 100)	(3 79)	(3 400)	(3 53)	?
Reiner	1	21	5 05	6 900	3 84			M
Cichus	1	21	5 05	8 000	3 90	6 700	3 83	M
Mädler	1	20	5 03	7 500	3 88	3 600	3 56	M

TABLE 4—*Continued*

Name	Class	Diameter (Miles)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Central Peak
Menelaus	1	20	5 03	6 600	3 82			M
Timaeus	2	20	5 03	(4 800)	(3 68)			M
Encke	4	20	5 03	2 000	3 30			1
Euler	1	19	5 00	6 700	3 83	2 300	3 36	1
Lambert	1	19	5 00	6 600	3 82	2 100	3 32	1
Archytas A	1	19	5 00	6 200	3 79			?
Vitruvius	4	19	5 00	4 400	3 64			1
Proclus	1	19	5 00	8 900	3 95			M
Theaetetus	1	19	5 00	8 400	3 92	3 400	3 53	
Callippus	1	18	4 98	9 700	3 99	7 900	3 90	1
Arago	1	18	4 98	(5 900)	(3 77)			1
Christian Mayer	2	18	4 98	(3 900)	(3 59)			1
Horrocks	1	18	4 98	8 000	3 90			M
Gassendi A	1	17	4 95	10 500	4 02			1
Ross	1	17	4 95	(4 800)	(3 68)			1
Grove	1	17	4 95	7 000	3 85			M
Sabine	4	16	4 92	2 800	3 45	(1 300)	(3 11)	1
Newton b	1	16	4 92	7 100	3 85			?
Schiaparelli	1	16	4 92	(6 700)	(3 83)	1 800	3 26	1
Delisle	1	16	4 92	6 200	3 79	1 800	3 26	1
Flamsteed	1	16	4 92	(6 200)	(3 79)	1 500	3 18	?
Grimaldi B	1	16	4 92	10 200	4 01			?
Langrenus M	1	16	4 92	9 500	3 98			?
Lalande	1	15	4 90	6 000	3 78			1
Clavius d	1	15	4 90	6 000	3 78	3 100	3 49	1
Heinsius d	1	15	4 90	8 700	3 94			M
Conon	1	15	4 90	6 400	3 81			1
Ritter	4	15	4 90	2 500	3 40			
Mösting	1	14	4 87	6 600	3 82	(1 600)	(3 20)	1
Kreiger	4	14	4 87			2 300	3 36	?
Picard	1	13	4 84	6 400	3 81	2 500	3 40	1
Dawes	1	13	4 84	(4 800)	(3 68)	2 600	3 41	?
Helicon	1	13	4 84	5 700	3 76			M
Triesnecker	2	13	4 84	(5 400)	(3 73)	2 300	3 36	1
König	1	12	4 80	(5 100)	(3 71)	(1 300)	(3 11)	?
Pierce	1	12	4 80	6 600	3 82	2 500	3 40	1
Bullialdus B	1	12	4 80	(5 200)	(3 72)	2 800	3 45	1
Pytheas	1	12	4 80	(4 800)	(3 68)	2 600	3 41	1
Bessel	1	12	4 80	4 300	3 63	1 600	3 20	
Diophantus	1	12	4 80	7 900	3 90	2 600	3 41	1
Macrobius a	1	12	4 80	9 500	3 98			?
Gemma Frisius d or G	1	12	4 80	8 900	3 95			M
Ramsden	1	12	4 80			2 000	3 30	
Milichius	1	11	4 76	(3 100)	(3 49)	(2 000)	(3 30)	?
Leverrier	1	11	4 76	6 200	3 79	1 500	3 18	1
Cassini A	1	11	4 76	7 400	3 87	(2 800)	(3 45)	1
Hortensius	1	11	4 76			1 600	3 20	1
Bode	1	11	4 76	5 000	3 70			1
Galileo	1	10	4 72			2 100	3 32	
Marius A	1	10	4 72	(7 400)	(3 87)	2 100	3 32	?
Gay Lussac A	2	10	4 72	4 800	3 68			1
Kunowsky	2	10	4 72			2 000	3 30	1
Macrobius B	1	9	4 68	(7 700)	(3 89)			?
Kepler C	1	9	4 68			1 800	3 26	?
Birt (N)	1	9	4 68	5 900	3 77	2 500	3 40	?
Messier A	1	9	4 68	6 700	3 83	2 100	3 32	?
Manners	1	9	4 68					1
Nicollet	1	8	4 62	4 000	3 60			?

TABLE 4—*Continued*

Name	Class	Diameter (Miles)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Central Peak
Beer	1	8	4 62	6 600	3 82	1 500	3 18	?
Picard d or A	1	8	4 62	7 500	3 88	2 000	3 30	?
Picard c or E	1	8	4 62	4 400	3 64			?
Gwilt	1	8	4 62			1 500	3 18	?
Beer A	1	8	4 62	2 000	3 30			?
Milichius A	1	7	4 57			3 100	3 49	?
Posidonius A	1	7	4 57	(3 800)	(3 58)	(2 000)	(3 30)	?
Pierce A	1	7	4 57			1 600	3 20	1
Caroline Herschel	1	7	4 57	3 000	3 48	2 300	3 36	1
Brayley B	1	6	4 51	3 000	3 48	1 000	3 00	?
Piazzi Smyth	1	6	4 51	3 500	3 54	2 100	3 32	?
(Cape) Laplace	1	6	4 51			1 600	3 20	?
Kies B	1	6	4 51	3 600	3 56			?
Carlini	1	5	4 41	2 000	3 30			1
Pico B	1	5	4 41			1 800	3 26	1
Galileo a	1	5	4 41			1 600	3 20	?
Luther	1	5	4 41			1 300	3 11	?
Murchison A	1	5	4 41	3 000	3 48			?
Diophantus A	1	5	4 41	4 800	3 68			?
Bullialdus F	1	5	4 41	3 800	3 58			?
SE of Purbach	1	5	4 41	1 650	3 21			?
Herodotus B	1	4	4 32			1 000	3 00	?
Copernicus D	1	4	4 32	4 200	3 62			?
Bullialdus I	1	4	4 32	3 900	3 59			?
Lubiniesky I	1	4	4 32	3 800	3 58			?
Birt D	1	4	4 32	1 950	3 29			?
Mairan A	1	3	4 20	4 000	3 60			?
S. of Plato F	1	3	4 20	1 400	3 15			?
E of Ptolemaeus	1	3	4 20	1 800	3 26			?
Piton A	1	2 6	4 14	1 630	3 21	560	2 75	?
Piton B	1	2 1	4 04	1 460	3 16	1 080	3 03	?
N of Lambert	1	2	4 02	2 800	3 45			?
W of Archimedes K	1	2	4 02	1 450	3 16			?
E of Archimedes	1	2	4 02	1 600	3 20			?
In Ptolemaeus	1	2	4 02	940	2 97			?
In Ptolemaeus	1	2	4 02	1 000	3 00			?
In Ptolemaeus	1	2	4 02	1 050	3 03			?
E of Ptolemaeus	1	2	4 02	1 700	3 23			?
Between Piton & Kirch	1	1 6	3 93	1 240	3 09	520	2 72	?
Between the above & Piton	1	1 3	3 84	1 030	3 01	300	2 48	?
W of P Smyth	1	1 3	3 84	1 240	3 09	300	2 48	?
Near Kirch	1	1 2	3 80	980	2 99			?
N of Piton	1	1	3 72	810	2 91			?
N of Kirch	1	1	3 72	1 000	3 00			?
S of Birt	1	1	3 72	1 600	3 20			?
In Alphonsus	1	1	3 72	950	2 98			?
In Purbach	1	1	3 72	940	2 97			?

flows covering much of the northern hemisphere These regions are rather dull in color The balance of the surface is much brighter and very considerably rougher MacDonald has called it the continental area, as contrasted with the maria or seas Scattered over the continental area are certain craters which are deeper relative to their diameters than others A relationship of this type also held good for the group he called walled plains On this basis the two main groups of craters were subdivided into two classes each—continental and normal For each of these four types an equation was derived relating diameter to depth for pits broader than 4 miles across, hence subdividing Ebert s work into four sections The resulting equations are

$$h = 0.378 d^{1/2} \tag{1}$$

for normal craters The depth of the crater is represented by h and the diameter by d both in kilometers

$$h = 0.378 d^{1/2} + 0.95 \tag{2}$$

for the continental craters

$$h = 0.234 d^{1/2} \tag{3}$$

for the normal walled plains

$$h = 0.234 d^{1/2} + 1.5 \tag{4}$$

for the continental walled plains

Similarly MacDonald found approximate equations for the relationship between diameter and height of the rim above the external plain This latter value is prone to underestimation because the reference points selected themselves often lie on the gentle slope

The two equations are

$$H = 0.153 d^{1/2} \tag{5}$$

for craters The value H represents the rim height in kilometers

$$H = 0.152 d^{1/2} \tag{6}$$

for walled plains except in each case, a few scattered continental objects which are high These equations and conclusions will again be examined in the light of an analysis of the data of Tables 4 5 and 6

The differentiation of craters and walled plains into normal and continental types was based on the assumption that because an apparent excess of relatively deep pits occurred primarily although not exclusively

TABLE 5

TERRESTRIAL METEORITIC CRATERS

Name	Diameter (Feet)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (feet)	log Rim Height (Feet)	Notes
Arizona	4 150	3 62	700	2 85	165	2 22	1
Odessa No 1	550	2 74	130	2 11	40	1 60	2
Odessa No 2	70	1 85	17	1 23			
Henbury No 13	30	1 48	10	1 00			

1 Depth determined from borings. Rim height is the present-day figure. It probably was nearly 300 feet high originally

2 Depth determined from shaft. Rim height given is most probable figure for original height.

TABLE 6

TERRESTRIAL EXPLOSION PITS (73)

Weight of Explosive (Tons)	Type of Explosive	Diameter (Feet)	log Diameter (Feet)	Depth (Feet)	log Depth (Feet)	Rim Height (Feet)	log Rim Height (Feet)	Notes
4 500	Ammonsulfatsalpeter	400	2 60	90	1 95			1
35	Ammonal	340	2 53	67	1 83			2
30	TNT	270	2 43	70	1 85	15	1 18	3
6	Gunpowder	171	2 23	28	1 45	8	0 90	4
600	Black powder	158	2 20	45	1 65	15	1 18	
85 3	Black powder Dynamite	150	2 18	60	1 78			
500	Ammonium nitrate	150	2 18	30	1 48			
15	Dynamite	108	2 03	20	1 30			5
12 5	Dynamite	90	1 95	15	1 18			6
11 2	Dynamite	75	1 88	30	1 48			6
9	Dynamite	60	1 78	10	1 00			
12	Dynamite	50	1 70	22	1 34			
10	Smokeless powder	50	1 70	18	1 26			
11	TNT	50	1 70	15	1 18			
10 12	Dynamite Black powder	50	1 70	15	1 18			
12	Dynamite	40	1 60	15	1 18			

1 Explosion at Badische Anilin & Sodafabrik, Oppau Bavarian Palatinate September 21 1921 60 per cent ammonium nitrate 40 per cent KCl or NaCl

2 Military mine crater (British) Hill 60, near Ypres.

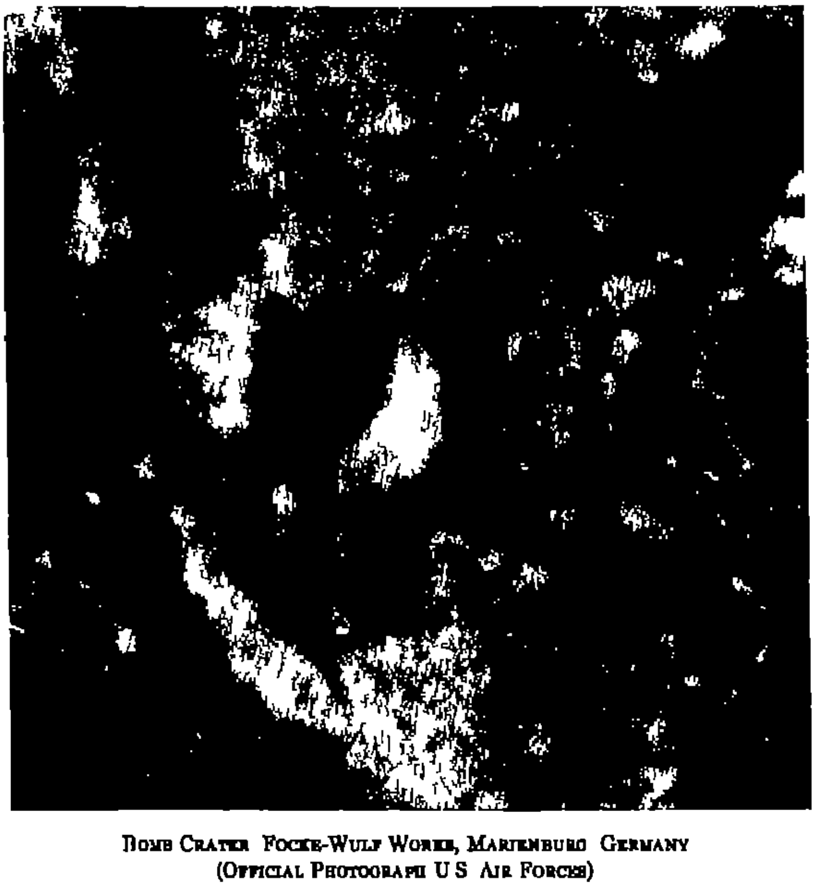
3 Military mine crater La Boisselle—two charges 60 feet apart

4 Oval average diameter used

5 Oval average diameter used In freight car

6. In freight car

PLATE X



Bomb Crater Focke-Wulf Works, Marienburg Germany
(Official Photograph U S Air Forces)

in one main region of the lunar surface the basic underlying cause was to be sought in the nature of the location That this is not the case will be made clear

From the work of Ebert and MacDonald it is now evident that there do exist definite relationships between the various dimensions of the lunar craters The general forms of the functions are known, but their exact natures are not yet defined It is of vital importance that these relationships be recognized but it is also clear that, unless the functions so derived can be extended to and correlated with phenomena well known here on earth no definite conclusions can be drawn regarding the mode of crater genesis To this end the literature concerning all forms of terrestrial craters pits calderas and sinks has been searched and much information on dimensions collected

When these data were assembled, it became patent that one type of crater and only one was of the proper form to suggest a similarity in origin to that of the lunar craters This is the simple explosion pit, the crater formed by a single application of explosive power Such a crater may be produced by bomb or shell military mine or meteorite the effect is the same

Fortunately during the recent war period tremendous amounts of knowledge were gathered concerning the properties of mortar and artillery shells and bombs, both army and navy Some of this information is now available to the public in censored form It is possible to compare diameters and depths of such craters but not to identify the weapon which produced the pit The values used in the next chapter and shown in Figure 12 have been taken from actual firing records of many hundreds of shells, ranging from the smallest mortar to the largest field-artillery piece, from tiny demolition bombs to blockbusters There are also records of numerous blasts from vast quantities of high explosive resulting in similar craters

In no other type of caldera known on earth can the relative dimensions consistently be correlated with those of the lunar craters The case for the explosive origin of the craters of the moon appears to be unassailable

CHAPTER 7

Correlations

IT IS one of the charms of the moon that it presents so many widely different views. Many of its craters are in a condition of pristine elegance, standing forth sharply and clearly from a less distinct background as though they had been formed but yesterday. Others seem more aged, their once perfect outlines marred by superimposed craters, usually smaller, which originated with no regard for the pre-existing object. All gradations of this sequence are readily recognized.

Another, and parallel, sequence is present. Many craters have been invaded by lava flows. Those in the regions now covered by the maria, except for the obvious postmare group, have been simply swamped by the vast liquid floods. In other cases the lavas have come from within the crater, have appeared, not with explosive violence, but calmly, as water rises in a well, as if the formation of the crater had fractured the crust and weakened it to allow the deeper juices to ascend to a stable level. Most of these cases are near a mare.

On the basis of appearance only, and with no association with measured dimensions, all craters for which fairly trustworthy measurements were available were grouped into four classes (Table 4). Class 1 contains only the pits which are definitely younger than their neighbors. Classes 2 and 3 contain craters which appear progressively older, having been more often violated by newer formations. Class 4 contains all those objects which have been modified by the inflow of lava. In addition, a very few of the most ancient rings, such as Catherina, have been lumped together in this group.

In making this classification no weight was given to the size or absence of a central peak. Instead, the emphasis was placed principally on the appearance of the walls with due record made of the frequency of the disturbing craters.

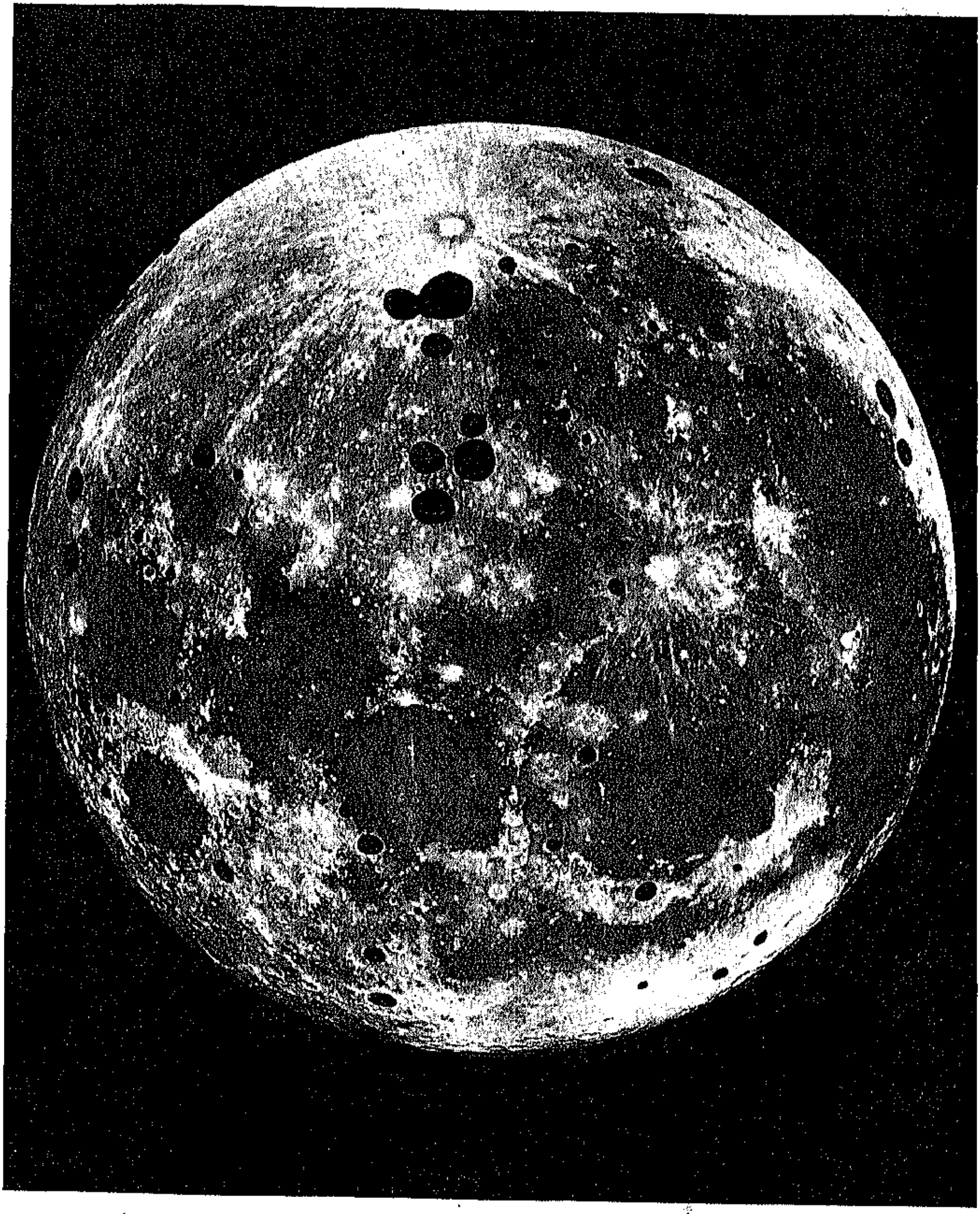
Those structures in Class 1 are more nearly representative of the se-

PLATE XI

Bomb Craters, Focke-Wulf Works, Marienburg Germany Craters Partially Filled by Seepage of Water and Silt Compare with Archimedes on Pl. VI

(Official Photograph U S. Air Forces)

PLATE XII



DISTRIBUTION OF LAVA-FILLED CLASS 4 CRATERS ON THE MOON; MOON, AGE 14.9 DAYS, MARCH 8, 1936 (LICK OBSERVATORY)

quence of crater shapes at the time of their formation than are the others. Hence the basic correlations with terrestrial objects should be attempted with them The simplest and perhaps most revealing relationship is that between the diameter and depth of craters MacDonald derived his four equations from craters larger than 4 miles in diameter Now additional measures down to craters only 1 mile across are available and Ebert s Rule may be reappraised on the basis of these new data and on the clarification incident to the separation of the craters into relative age groups

The spread in measured lunar crater diameters is about 150 1 The largest craterpit man made is thirteen times smaller than the least in the lunar list Numerous others range downward over an additional factor of 100 There is a similar vast compass in crater depths To show such divergent dimensions on a single chart, it is necessary to use a log log scale Figure 12 illustrates the beautiful relationship between the lunar craters on the upper right and shell bomb and explosion pits on the lower left, the co-ordinates being expressed as logarithms of the diameters and depths in feet The dimensions used here are in all cases the apparent dimensions measured from the top of the rim rather than at ground level

Unfortunately these two groups do not overlap and thus establish the explosive one shot nature of the lunar pits However, nature has stepped into the breach and obligingly furnished four meteoritic craters whose dimensions have been carefully measured Many other such craters are known of course but have not been thoroughly investigated Two of the four craters Henbury No 13 and Odessa No 2 have diameters and depths so related that the two points representing them in Figure 12 lie well within the scatter of the points for the terrestrial explosion pits Another Odessa No 1 extends the curve toward the lunar points Beyond Odessa No 1 lies the only gap in the picture but here again fortune is kind for the space is bounded on the upper side by the great Arizona meteorite crater The point representing this Coon Butte pit lies immediately below but well within the lateral scatter of the points for the lunar craters There is thus a very smooth curve which represents equally well the largest Class 1 lunar crater and the smallest terrestrial explosion pit These two groups tied together perfectly by craters of known meteoritic origin form a relationship which is too startling too positive to be fortuitous The equation

$$D = 0\ 1083\,d^2 + 0\ 6917\,d + 0\ 75 \qquad (7)$$

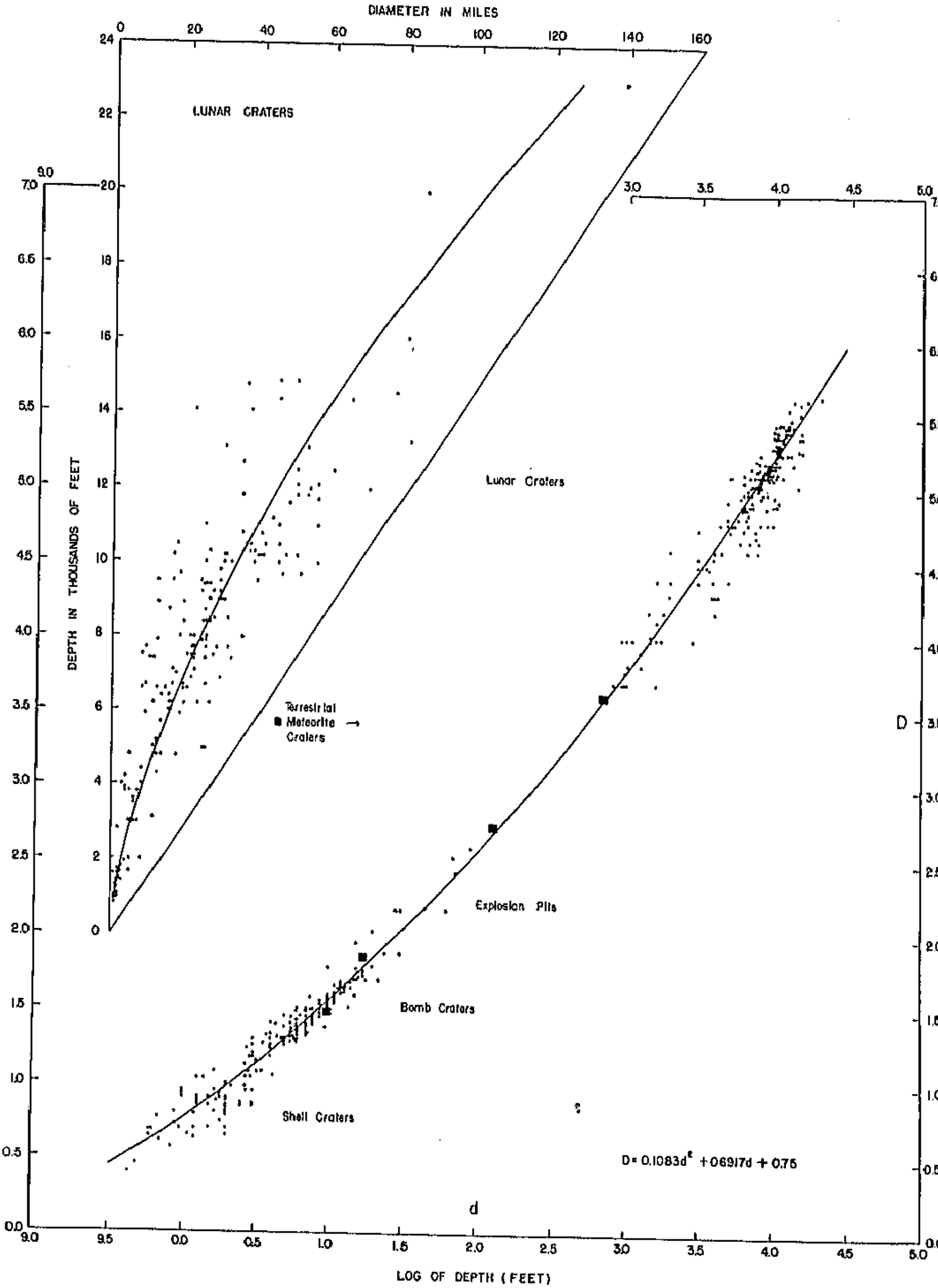


FIG. 12.—Relationship between diameter and depth of terrestrial explosion craters, terrestrial meteoritic craters, and lunar craters of Class 1.

a simple quadratic gives an excellent fit where

$$D = \log \text{diameter (feet)}$$

$$d = \log \text{depth (feet)}$$

Figure 13 *A B C* shows on the same scale the curve from equation (7) compared in succession with the lunar craters of Classes 2 3 and 4 It is seen that these groups in order, become more and more shallow The slope of the curve indicated by the points in each case is roughly parallel to the curve for the Class 1 craters, hence the larger craters of the other three classes lose in depth at the same relative rate as do the smaller objects but more rapidly in absolute dimensions

In Figure 13 are also shown for comparison the four curves found by MacDonald (70) These functions were derived only for the craters larger than 4 miles in diameter or $D = 4\ 41$ They have been extended to show that the curvature is in the wrong direction and that they cannot be made to represent the terrestrial data which have been shown to be consistent with the lunar crater dimensions These functions represent the best previous effort to analyze the data on crater dimensions and hence to indicate a possible mode of origin The limitations of this attempt are apparent The bold step, the tying in of the lunar data with terrestrial knowledge was not made The try failed as have all previous attempts to set up relationships which would indicate the cause of the surface features of the moon because it never passed the point of ambiguity

The argument over the mode of origin of the moon s craggy formations has raged unabated since Galileo first turned his tiny telescope toward the moon and found ring mountains over three hundred years ago Numerous theories both wild and sound have been advanced to explain these objects In most cases they died as rapidly as they were born for obvious reasons The same elements exist on the moon as on the earth The same physical laws are operative on both worlds Therefore it is only logical to seek the explanation of lunar formations in terms of things known to be possible here on earth rather than to delve into the realm of the fantastic and postulate strange new processes albeit weird variations of recognized terrestrial mechanisms The second stage should not be entered until the possibilities of the first are exhausted It is in this step that previous studies have failed It is in this step that the main curve of Figure 12 gives the first unmistakable clue

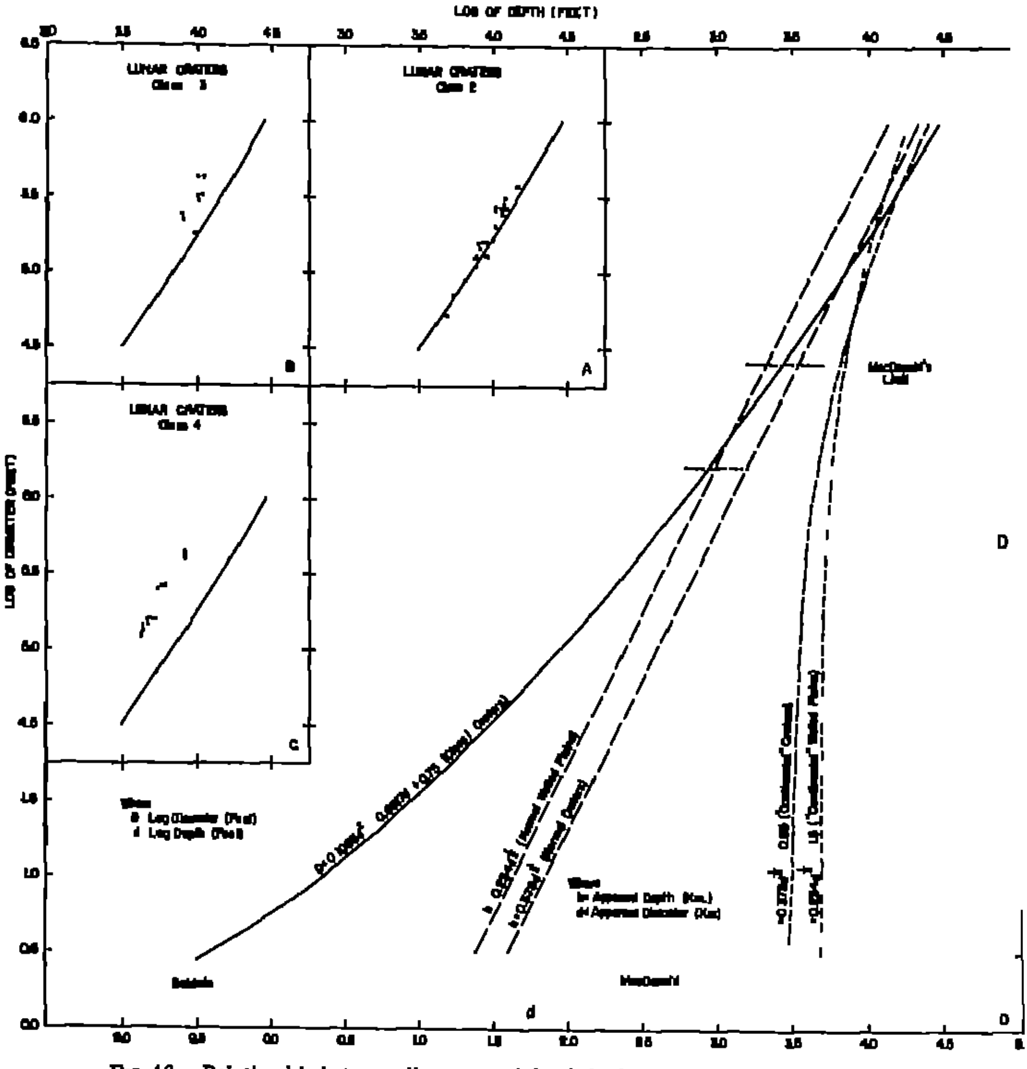


FIG 13 —Relationship between diameter and depth for lunar craters of Classes 2 3 and 4

On earth we know and are familiar with the effects of high explosive It is used in numerous military and commercial applications The laws governing its effects, particularly with regard to its crater forming powers, are understood primarily because of work done by the armed forces

The smallest mortar shells fuzed delay make craters less than 3 feet across and less than 1 foot deep From these insignificant pits there is a smooth, continuous progression in size first, to the larger shell craters then to those from bombs and other great explosions Overlapping the portion of the curve defined by the man made pits is the section delineated by the terrestrial meteoritic craters which are known to be due each to a single explosion and hence the verifiable portion of the curve is moved upward to a place where the scatter of points representing the lunar craters forms a logical and entirely consistent extension

The only reasonable interpretation of this curve is that the craters of the moon vast and small, form a continuous sequence of explosion pits each having been dug by a single blast No available source of sufficient energy is known other than that carried by meteorites

The observed relationship between diameters and depths is clearly of the type to be expected for explosion pits It can also be shown that there exist other correlations between crater forms and dimensions which may be extended from the man made craters through the terrestrial meteoritic craters and the lunar craters

A shell or bomb is so constructed that the greatest fragmentation and the greatest blast effect occur primarily in the plane of its equator In spite of this the form of the crater produced by a shell or bomb is essentially circular The rim may be slightly oval or even tend toward polygonalism This holds true regardless of the angle of fall almost down to the limiting case in which a ricochet occurs before the detonation The various terrestrial meteoritic craters are undoubtedly formed by the nearly horizontal blasts of superheated compressed air and other vaporized matter As has been shown in the majority of cases oblique impacts lead to nearly circular craters which may tend toward a multisided shape Exactly the same description fits the lunar craters

All terrestrial explosion pits are produced by the violent displacement of earth materials upward and outward, thus forming a sunken pit and a surrounding low rim This rim is concentric with the pit is steep on the inner face and gradually dips down to the level of the outer plain The

maximum height of the rim occurs at the upper edge of the apparent crater and this height increases with increasing crater diameter Schröter s Rule finds an exact counterpart here for the ejected rim materials certainly would fill the pit if replaced including of course any fragmental pieces blown so far that they seem distinct from the rest of the rim This description applies equally well to the lunar craters of Class 1 and with decreasing rigor to the other three classes

A definite and simple relationship exists (Fig 14 A) between the diameter and rim height of all explosion pits and lunar craters

$$E = -0\ 097D^2 + 1\ 542D - 1\ 841 \tag{8}$$

where

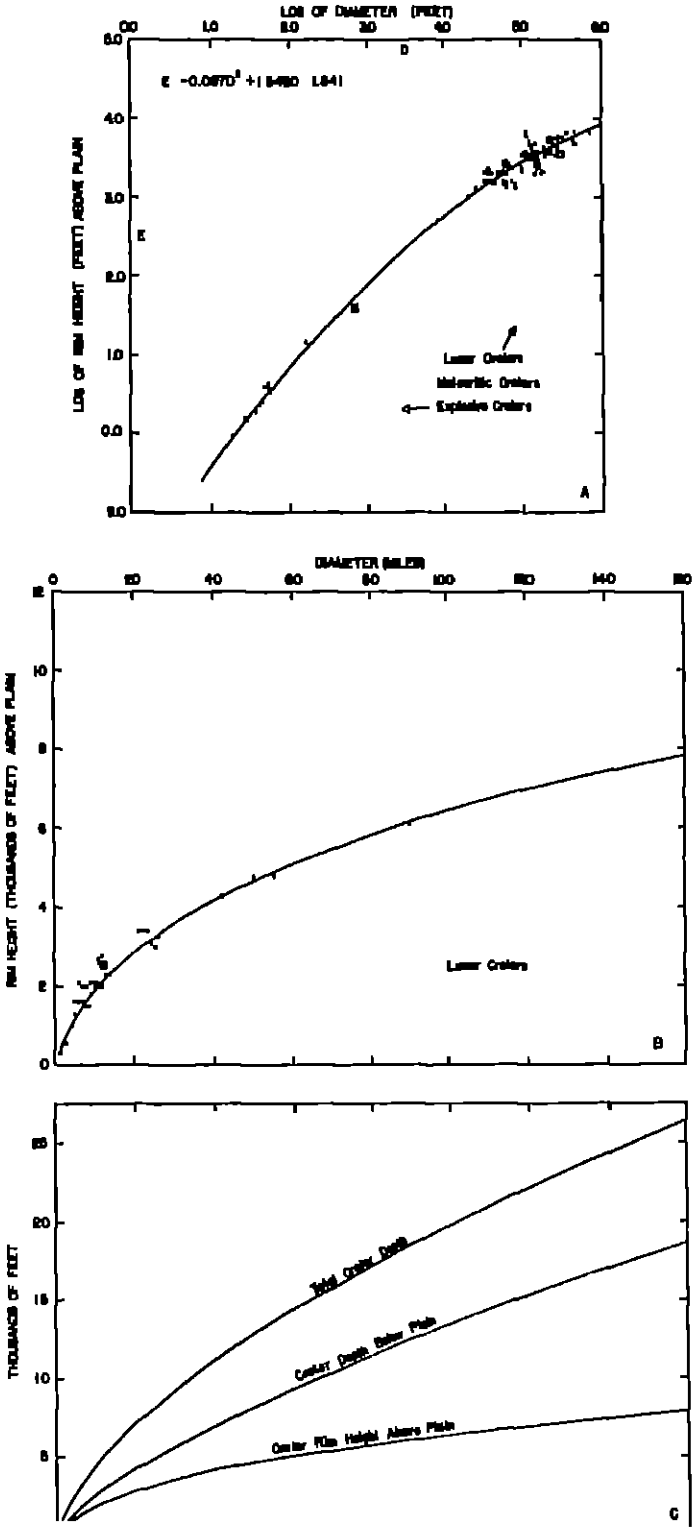
$$E = \log \text{rim height (feet)}$$

$$D = \log \text{diameter (feet)}$$

The difference between the apparent crater depth as derived from equation (7) and the rim height from equation (8) yields the true crater depth below ground level (Fig 14 C)

Figure 7 shows that to a first approximation the form of any Class 1 crater is that of a cup It may be represented approximately by the segment of a sphere whose size is defined by the internal depth of the subsurface crater and its surface diameter Equations (7) and (8) may be used to give the observed mean values of real crater depth and rim height as functions of diameter From measurements of numerous craters it was found that the width of the rim is roughly one-quarter of the crater diameter On the average the central peak rises half the way from the crater floor to the ground level These assumptions allow a calculation of the volume of the displaced material and also a theoretical determination of the rim height on the basis of equality of volumes If the calculated and observed rim heights agree it is a clear confirmation of Schröter s Rule As may be seen over the entire range covered by the Class 1 craters the agreement between calculated and observed lunar crater rim heights is excellent and Schröter s Rule is completely confirmed (Table 7)

It is important to know whether or not the depth at which an explosion takes place has a great bearing on the form of the resultant apparent crater Such an analysis cannot be made with respect to the lunar craters or to the terrestrial meteoritic craters However it has been the subject of


LOG OF DIAMETER (FEET)
LOG OF RIM HEIGHT (FEET) ABOVE PLAIN
Lunar Craters
Meteoritic Craters
Explosive Craters
A
DIAMETER (MILES)
RIM HEIGHT (THOUSANDS OF FEET) ABOVE PLAIN
Lunar Craters
B
THOUSANDS OF FEET
Total Crater Depth
Crater Depth Below Plain
Crater Rim Height Above Plain
C

numerous studies of bombs and shells and for such explosion pits the an swer is definitely No for a wide range in depth of explosion for a con stant explosive charge The linear dimensions of the craters are directly associated with the violence of the explosions and with the depths at which they occurred but the relative dimensions are almost independent of the depth

Figure 15 illustrates for a constant mass of explosive the experimentally determined changes in crater size and form as the center of explosion given by the star is placed at different distances below ground The verti cal and horizontal scales are the same in all cases The shaded areas repre- sent loose material

Figure 16 combines the data from Figure 15 The vertical and horizon tal scales are the same although the vertical scale is used as a pure num

TABLE 7

CALCULATED AND OBSERVED RIM HEIGHTS

Crater Diameter (Miles)	Real Crater Depth (Feet)	Volume (Cubic Miles)	Rim Height (Feet) (Calc.)	Rim Height (Feet) (Obs.)
0 1	96	$7\times10^{-[illegible]}$	68	43
1	516	$3\times10^{-[illegible]}$	277	355
20	4 200	92	2 200	2 800
40	7 000	615	3 700	4 200
60	9 300	1 850	4 900	5 100
80	11 500	4 050	6 100	5 900

ber for the curve which gives the ratio of diameters over depths It is seen that until the depth of explosion increases almost to the point where a *camouflet* is formed the relative dimensions of the apparent crater are nearly constant. Hence for ordinary terrestrial explosions the form of the crater is not sensitive to moderate changes in the depth of explosion until the explosion occurs at a depth greater than one half the diameter of the resultant apparent crater

It is probable although not demonstrably so that the same rule is fol lowed in the cases of the larger terrestrial meteoritic craters and the lunar craters.

Any meteorites which formed lunar craters undoubtedly arrived with a considerable spread in velocities and hence they penetrated the moon s crust for different distances However, since the form of the crater is near ly independent of the depth of explosion at least for the smaller craters

such an effect should not be apparent in the diameter-depth relationship, nor is it observed.

The exact depth to which a given mass would plunge is difficult to calculate. It is clear that a minimum figure can be derived. The meteoritic mass, as long as it is moving faster than the velocity of a shock wave in the crust, 5.5 miles per second, will compress matter ahead of it. The combined mass, meteorite plus plug, will slow up rapidly with a maintenance of total momentum as the plug grows larger. Essentially no momentum will be lost during this interval. The distance h from the ground to the base of the compressed matter at the instant that this velocity is reached may be expressed as

$$h = \frac{4r}{3}\frac{\rho_1}{\rho_2}\frac{(v-5.5)}{5.5} \tag{9}$$

where

r = The radius of the (spherical) meteorite
ρ_1 = The density of the meteorite
ρ_2 = The density of the ground layers
v = The striking velocity in miles per second

For $\rho_1 = 7.9$ and $\rho_2 = 2.67$, h and v are related as shown in Table 8. After the shock wave velocity has been reached, the combined mass would come quickly to a halt, and therefore the figures of Table 8 represent conservative minimums.

TABLE 8

PENETRATION OF METEORITES INTO GROUND

	h
10	$3.2r$
15	$6.8r$
20	$10.4r$
35	$21.2r$
50	$31.9r$

It may be pointed out that the larger masses penetrate more deeply than smaller masses moving at the same velocity but that the differences are not great, for the depth of penetration is proportional to the radius but the mass increases as the cube of the radius.

Wylie (40) has calculated the probable ranges in mass and radius of the body which produced the Arizona crater on the basis of extrapolations from mine explosions. He finds, for a spherical body, that a surprisingly small mass is needed.

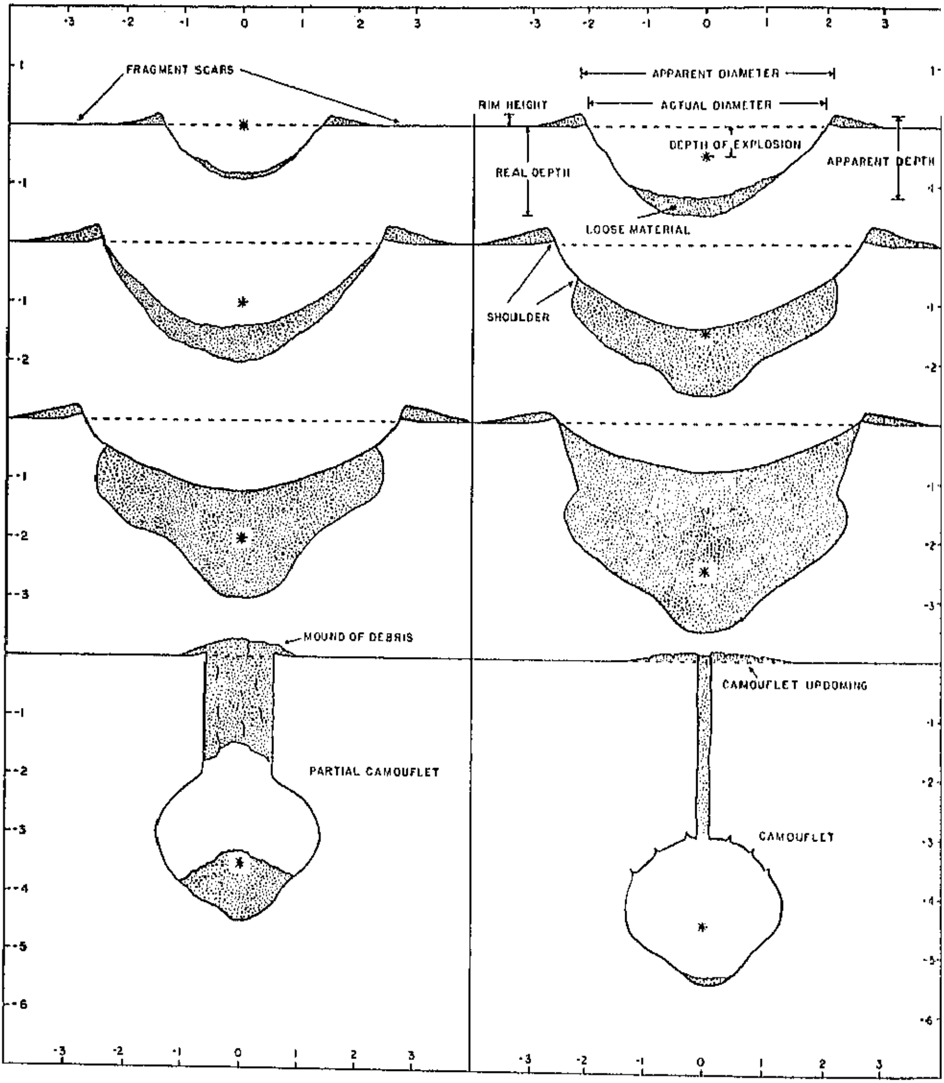


FIG. 15.—Schematic relationships between dimensions and depth of explosion for terrestrial craters

For an assumed $v_0 = 15$ miles per second the meteorite would have punched a hole at least 67 feet deep. It seems certain that Wylie's estimate of the possible mass range for the Canyon Diablo meteorite is approximately correct. Therefore the radius of the body is closely defined. We are forced to the conclusion that either the explosion centered close to the surface or else the body struck with a very high velocity. A radius of 20 feet and a striking velocity of 50 miles per second, the maximum possible for a solar system meteorite, would lead to a depth of over 600 feet. This would have to be reduced somewhat as the angle of fall was perhaps 45° from the vertical.

The above figures probably represent limiting conditions and yet the depths found are reasonable. It seems clear that even for the larger mete-

TABLE 9

VELOCITY VS MASS OF ARIZONA CRATER METEORITE

v_0 (mps)	v (mps)	Mass (Tons)	Radius (Feet)
7	5.3	29,000	32.0
10	7.1	16,000	26.1
15	10.0	8,000	20.9
20	12.6	4,900	17.8

v_0 = The velocity just outside the atmosphere
v = The striking velocity

orites capable of producing the lunar craters the explosion focuses are not far below the surface, the masses thus come to rest in a small fraction of a second and hence the energy is rapidly released—all of which are factors necessary to the formation of an explosion crater rather than of a *camouflet*.

The form of the Odessa No. 1 crater (Fig. 8) is typical of one produced by a shallow explosion (Fig. 11). This is confirmed by the undisturbed character of the subjacent Triassic shale some 200 feet down.

It is not readily apparent that the curvature of the moon's surface has a very definite effect on the shape of the craters. Figure 17 shows the form of five typical craters of Class 1 drawn from the data of Figures 12 and 14. For each crater the horizontal and vertical scales are identical, but in each case the scale has been changed in inverse proportion to the actual diameter so that all craters have the same linear width in the illustration.

If a chord equal in length to the crater diameter be drawn through the

crust of the moon the depth of the chord center below the spherical sur face is always less than 1 mile for diameters up to 90 miles, and the effect of such an amount of curvature is negligible on the appearance of the crater For larger craters this chord depth increases more rapidly than the real depth of the crater below the surface and the two become equal at a diameter of 180 miles (Fig 18) The effect of the moon s curvature on larger craters then, is to cause their floors to be more and more nearly flat,

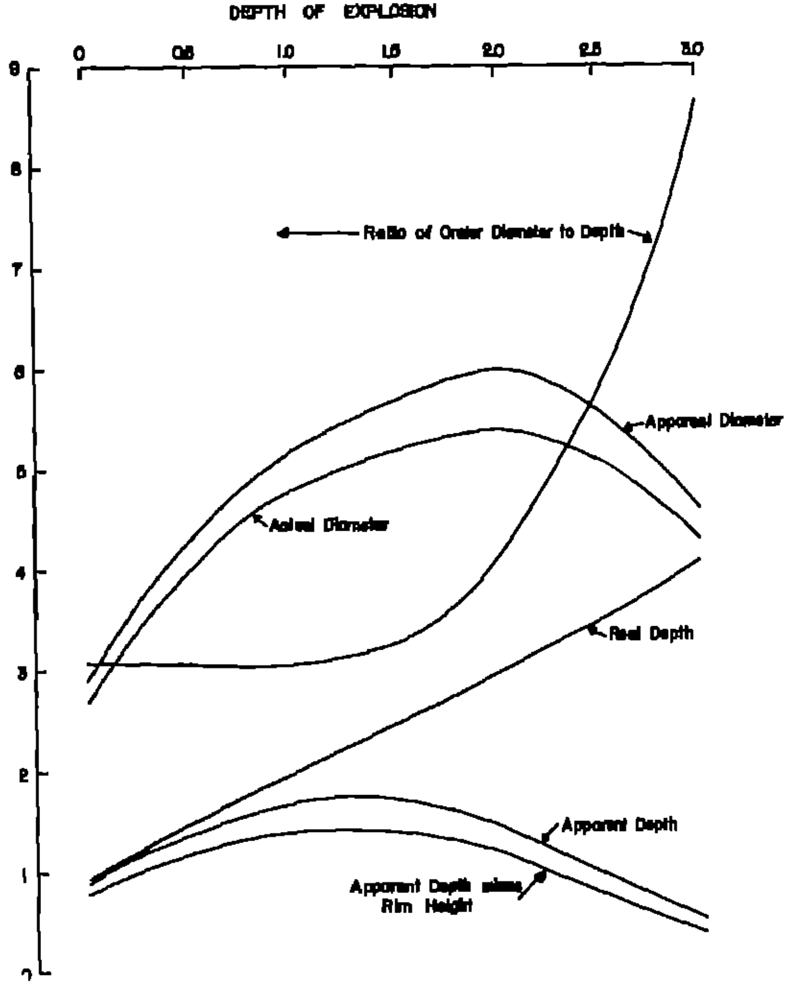


FIG 16.—Changes in crater dimensions as functions of depth of explosion (Data from Fig 15.)

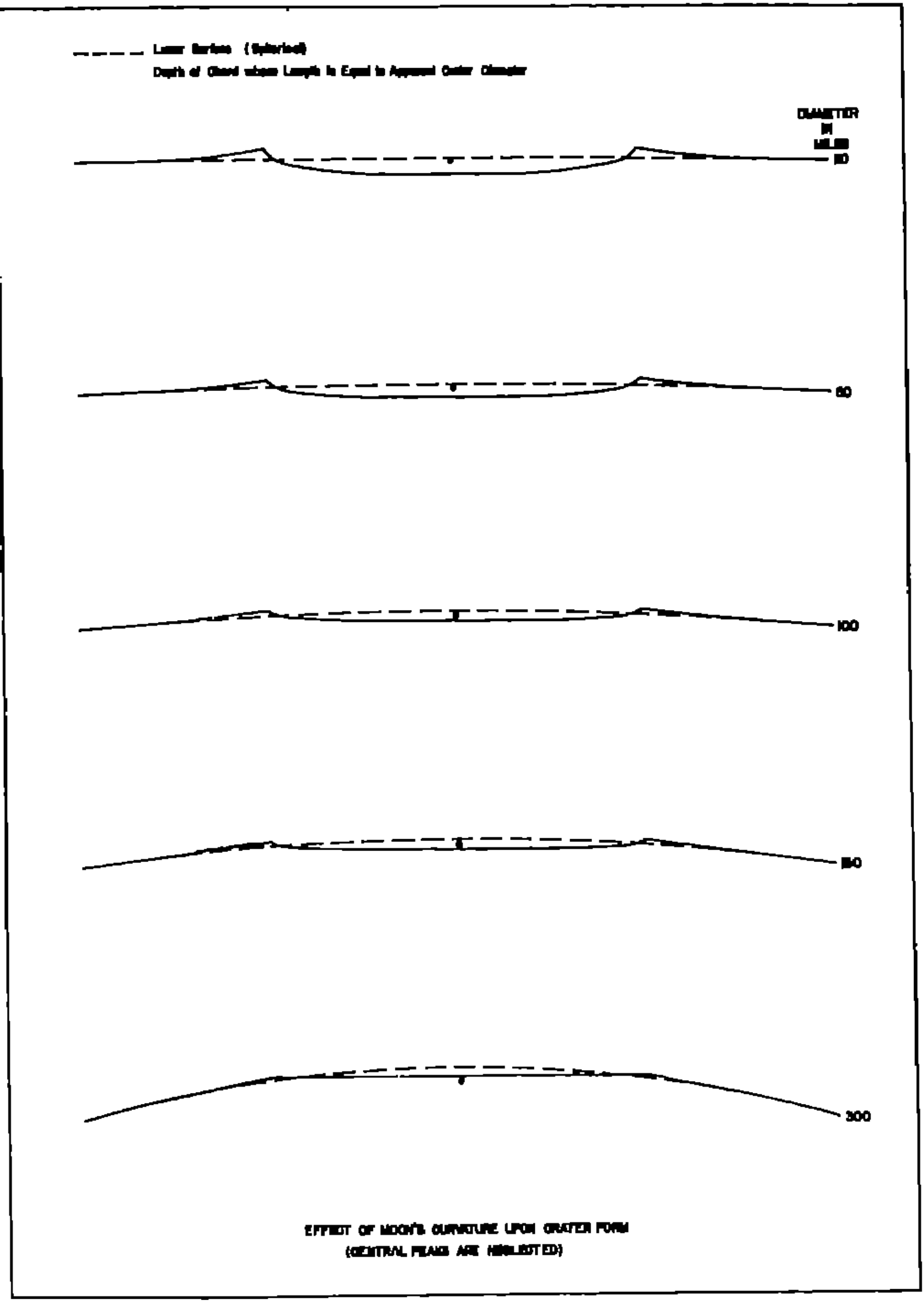


FIG. 17 —Changes in lunar crater form as a function of diameter The effect of curvature of the moon s surface is shown

and for craters larger than 180 miles in diameter (chap 11) the floor would actually be convex rather than concave if the diameter depth curve from Figure 12 is followed For a crater 300 miles across even the rim would seem to disappear and it would appear only as a nearly flat spot on the sphere This is shown by the bottom drawing of Figure 17

In this analysis it has been assumed that no central peak was present

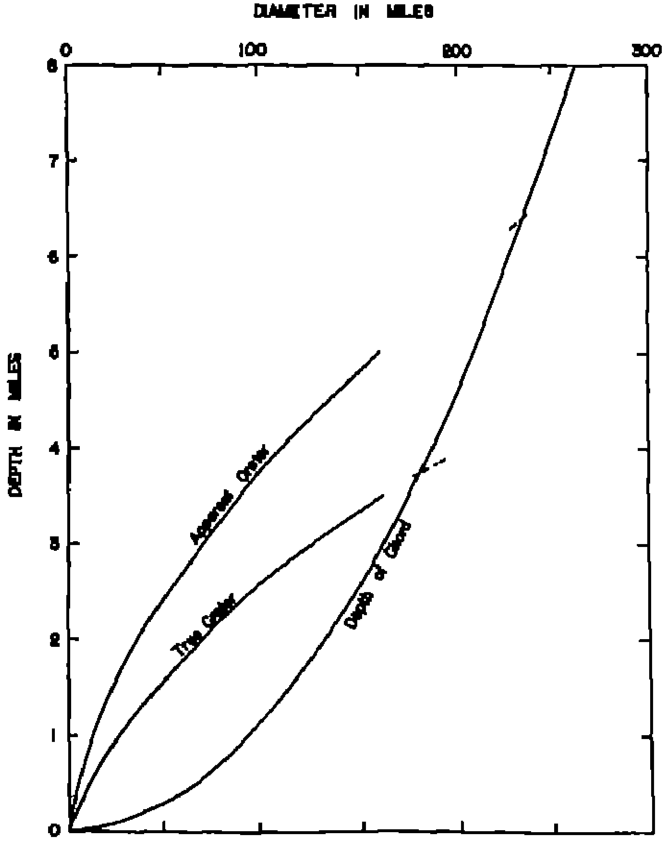


FIG 18—Effect of curvature of moon's surface upon crater form

If one were present the convex condition would be reached at a smaller diameter than 180 miles

The geometry of the situation seems to indicate an upper limit of possibly 180 miles for the diameter of normal craters For explosions more violent than those which could cause a normal crater the resultant pit would assume the appearance more of a flattened spot on the lunar surface

than of a true crater The largest of the observed craters of normal type is Clavius with a diameter of 146 miles Several others are not much inferior Bailly at 160 miles may perhaps be included in this group Numerous larger objects all associated with the maria, are known and do suggest that initially they were of the deduced form

A correlation may be attempted between the diameter and depth of certain volcanic craters in a manner similar to that done for the lunar craters It is immediately found that the normal pit of explosive vulcanism does not yield a smooth correlation of the proper type For example, Vesuvius (23) after the great eruption of 1906 was 2 000 feet deep but only 2 200 feet across By contrast the pit of Bandai San (23) in Japan was 8 000 feet wide and 1 200 feet deep The modern active stratovolcanoes go up to about 20,000 feet in height but with relatively small summit craters the walls of which, inside and out are close to the angle of repose Extinct Aconcagua in the Andes is still over 23 000 feet high, but its crater has been eroded away There is no similarity between such as these and the craters of the moon

The terrestrial volcanic form nearest the lunar craters in appearance is the caldera of collapse Many samples are known and relative dimensions have been collected in Table 10 The figures give clear evidence of a generally elliptical shape and the pits are on the average only about one-fifth as deep relatively as the lunar craters It is the general but not universal rule that the caldera floors are raised rather than sunken with respect to the surrounding ground level

Figure 19 shows that, while there may be a slight tendency for the larger collapse caldera to be deeper than the smaller the trend is not pronounced and the scatter is excessively large These pits have not been greatly eroded and filled in as the local deposits of pumice and other pyroclastic materials make clear

In spite of these definite points of difference the collapse caldera offer the closest approximation in appearance of any of the earthly volcanic forms to the lunar craters the terrestrial meteoritic craters and the known explosion pits The little known cryptovolcanic structures may be exceptions to this rule Nevertheless the divergences are so great as to make it certain that the lunar craters are not collapse calderas although certain structures on the moon give evidence of sinking motions after their formation Therefore it is apparent that further to pursue the will o the wisp

of a dominant-process lunar vulcanism of the type of any known terrestrial vulcanism is futile the extensive and numerous geologic studies have not yielded a similar development past or present

To claim that the moon s craters are volcanic is tantamount to postulating an entirely new entirely hypothetical mode of origin and to fly in the face of the fact that a known process is completely able to explain the vast majority of observed lunar features.

TABLE 10

MENSURATION OF TERRESTRIAL COLLAPSE CALDERA (23)

Name	Major Diameter (Miles)	Minor Diameter (Miles)	Depth (Feet)	log Diameter (Feet)	log Depth (Feet)
La Caldera, Canary Islands	4	?	4 000	4 30	3 60
Crater Lake, Ore.	6	4	3 000	4 40	3 48
Valles N.M	18	16	1 000	4 95	3 00
Aniakchak Alaska	6 7	5 7	2 500	4 48	3 40
Krakatau off Java	4 3		1 200	4 32	3 08
Aira, Japan	15	14	1 500	4 88	3 18
Kikai Japan	14	8	1 200	4 81	3 08
Towada Japan	7		2 000	4 56	3 30
Lago di Bolsena, Italy	11	?	1 500	4 70	3 18
Blue Lake Mt. Gambier South Australia	0 25	?	500	3 20	2 70
Knebel See Iceland	4 5		1 300	4 36	3 11
Rudloff Crater Iceland	1 5		740	3 90	2 87
Mokuaweoweo, Hawaii	3 5	2	600	4 18	2 78
Nemrut Gölü, Turkey	2 5		2 000	4 08	3 30
Newberry Caldera Ore	5	4	1 500	4 40	3 18
Idjen Caldera, Java	12	10	1 500	4 78	3 18
Katmai Alaska	3		3 000	4 18	3 48
Kilauea, Hawaii	3 5	2 5	450	4 18	2 65
Halemaumau Hawaii (1940)	0 6		800	3 51	2 90
Aso Japan	16	10	?		
Ibusuki Japan	16	7	?		
Kuttyaro Japan	16	12	?		
Akan Japan	15	8	?		
Inawashiro, Japan	20	9	?		
Volcano Bay Japan	28		?		
Batoer A, Bali	8 5	6	?		
Batoer B Bali	4 5	?	?		

The central peak of the lunar crater is a well nigh universal feature In general it is placed at the exact center of the floor but many examples of slightly eccentric locations are to be found, particularly among the larger craters A decided misapprehension is prevalent concerning the nature of these peaks The term 'central peak of a crater' automatically brings to mind a volcanic cone within a larger volcanic crater In spite of this association the great majority of such double crater forms here on earth are

nonconcentric, the secondary peak usually arising somewhere near one edge of the main crater, in contradistinction to the usual lunar form. Wizard Island in Crater Lake, Oregon, furnishes a nice example of the terrestrial form.

In all volcanic cones, whether they be cinder, pyroclastic, or stratovolcanic, ejected material has assumed approximately the angle of repose. The result is that smoothly symmetrical cones develop. The majority of volcanoes fall into these three classes, and the form is characteristic. Wherever in the world they appear they assume similar outlines.

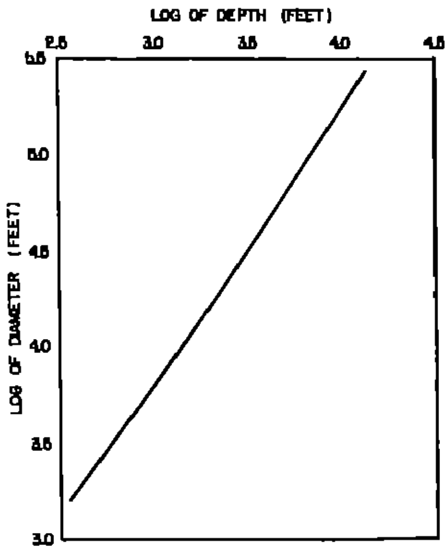


Fig. 19.—Relationship between diameter and depth for terrestrial calderas of collapse. Line gives same relationship for lunar Class 1 craters. Agreement is poor.

By contrast, the central peaks of the moon's craters rarely, if ever, resemble a volcanic cone. Instead they are almost invariably craggy and irregular, blocklike, giving the impression of having been placed in a hopelessly jumbled and chaotic mass by some gigantic force operating concentrically with the crater walls. The irregular nature of these central peaks is clearly shown in the larger craters, where a majority have not one but several distinct crests, each of which is an irregular structure not at all like a built-up cone. In many cases, Theophilus for example, the mountain base completely fills the floor of the crater, and even in the smaller objects the angle of repose is rarely reached.

On the average the larger the crater the larger the central peak or group of peaks but wide graduations exist In a small minority of the cases no central elevation can be found In others it is very tiny while in many it is prominent The crater Moretus has the highest peak known, with a measured altitude of 7 500 feet above the floor

It is a powerful argument against the volcanic nature of these formations that, of the numerous craters which show central peaks no single instance is known of a mountain top which even reaches to the level of the surrounding external plain In all certainty the central uplift is a sub-surface structure which originated in the single explosion which formed the crater Its presence may probably be attributed to two factors The impact of a high velocity meteorite is accompanied by the transference of a great deal of momentum to the compressible surface layers This results in a rebound which may become fixed as a structural dome Second the explosion is initiated underground and rarely is the loose detritus cleaned out of the pit Some of this breccia may remain raised in the crater bottom Contrary to an often expressed opinion a central peak of this type is commonly found in bomb craters especially those from bombs whose fuzes are set for delay rather than for superquick

Absence of the central elevation seems to be a normal characteristic of a small percentage of all craters but this is not a feature which divides two different types of craters The pits without peaks represent the limiting cases of a broad distribution of crater forms The other crater details are not closely correlated with the central peak dimensions

The smaller a crater is the harder it is to detect in it a central peak This is also true for craters near the limb In Table 4 the presence complexity or absence of a central elevation is noted A brief tabulation of the results (as shown in Tables 11 and 12) is rather informative

These data are presented graphically in Figures 20 and 21 In the former they are shown as actual numbers of craters with and without central peaks as a function of diameter group Shaded areas increasing toward the smaller crater sizes, mark the objects for which this knowledge is not available In both figures charts are given for each of the four classes of craters In Figure 21 the numerical data of Table 12 given in percentages of craters with and without central peaks, are shown Again the shaded areas represent the cases in which it is uncertain as to whether or not the crater has a central elevation

TABLE 11

Statistics on Central Peaks

Diameter (Miles)	Group	Class 1 (1)*	Class 1 (2)†	Class 1 (3)‡	Class 2 (1)	Class 2 (2)	Class 2 (3)	Class 3 (1)	Class 3 (2)	Class 3 (3)	Class 4 (1)	Class 4 (2)	Class 4 (3)
101–146	1	0	0	0	2	2	0	2§	1	0	4	1	0
81–100	2	2	1	1	2	1	0	3	1	1	4	2	0
71– 80	3	2	2	0	1	1	0	1	0	0	7	6	0
61– 70	4	2	2	0	2	0	0	1	1	0	4	2	0
56– 60	5	5	4	0	1	0	1	3	0	2	3	0	0
51– 55	6	4	4	0	5	4	0	2	2	0	3	2	0
46– 50	7	8	6	0	3	3	0	2	2	0	4	2	0
41– 45	8	7	6	0	2	1	1	2	0	0	2	0	0
36– 40	9	12	9	0	5	2	0	1	0	0	3	1	1
31– 35	10	9	7	0	6	3	0	4	2	1	7	2	0
26– 30	11	21	17	3	4	1	0	5	1	1	9	4	0
21– 25	12	27	20	3	6	3	1	0	0	0	9	3	1
16– 20	13	19	13	5	2	2	0	0	0	0	3	3	0
11– 15	14	22	16	4	1	1	0	0	0	0	2	1	1
6– 10	15	22	3	17	2	2	0	0	0	0	0	0	0
1– 5	16	34	2	32	0	0	0	0	0	0	0	0	0

* Number of craters (Table 4)
† Number of craters with central peaks.
‡ Number of craters listed as (Central Peak)?
§ Schiller is composite crater

TABLE 12

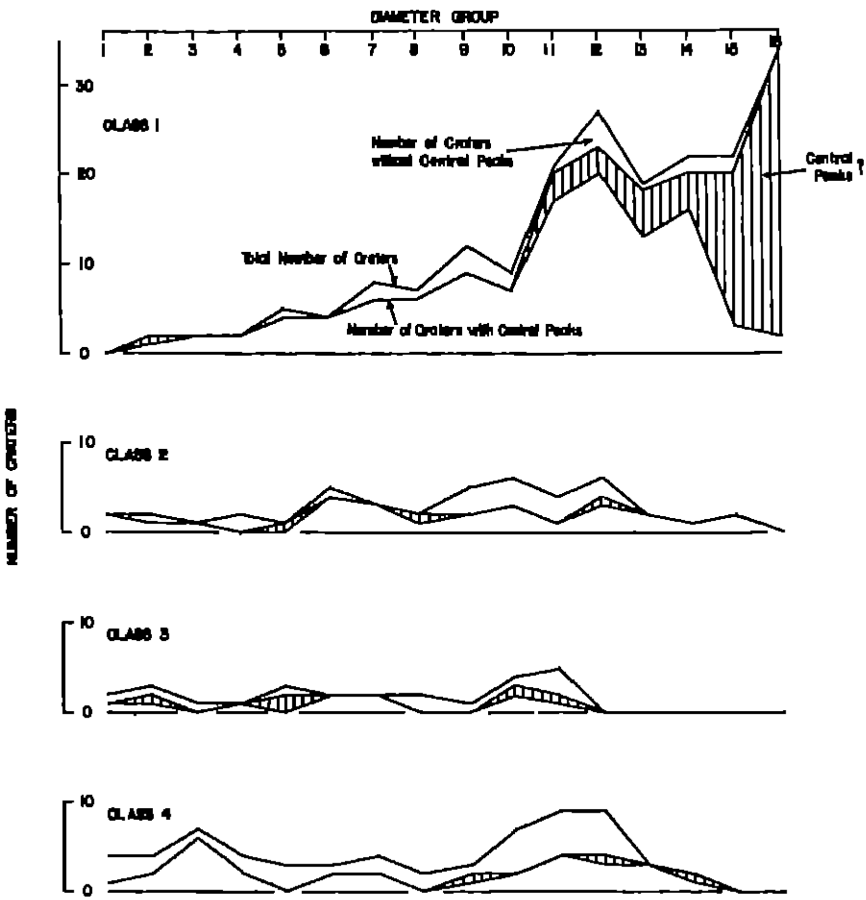
Percentage of Craters with Central Peaks

Group	Class 1 (1)	Class 1 (2)†	Class 2 (1)	Class 2 (2)	Class 3 (1)	Class 3 (2)	Class 4 (1)	Class 4 (2)
1			100	0	100‡	0	25	0
2	50	50	50	0	33	33	50	0
3	100	0	100	0	0	0	86	0
4	100	0	0	0	100	0	50	0
5	80	0	0	100	0	67	0	0
6	100	0	80	0	100	0	67	0
7	75	0	100	0	100	0	50	0
8	86	0	50	50	0	0	0	0
9	75	0	40	0	0	0	33	33
10	78	0	50	0	50	25	28	0
11	81	14	25	0	20	20	44	0
12	74	11	50	17			33	11
13	68	26	100	0			100	0
14	73	18	100	0			50	50
15	14	77	100	0				
16	6	94						

* Percentage of craters with central peaks
† Percentage of craters with (Central Peak)
‡ Schiller is composite crater—not used

There is no statistically valid trend to be found in the percentage of craters with central peaks for any crater class However the percentage of craters which do possess this feature decreases steadily from Class 1 through Class 4 It was shown previously that the average crater depth decreased from class to class in the same order and there is probably a generic connection between these two sets of facts The average percentages observed are 86, 63 50, and 48 respectively

The idea of the volcanic nature of the central peaks of the lunar craters dies hard Pickering (74) has reported the identification of craterpits in the



CENTRAL PEAK STATISTICS

FIG 20—Relationship between numbers of craters with and without central peaks as a function of crater diameter Data given for each class of crater

central peaks of twelve craters They range from ½ to over 2 miles in diameter and hence are among the tiniest observable craters

Campbell (75), in speaking of these discoveries says 'Must we not agree that the unquestioned existence of craterlets in the summits of central crater peaks is absolutely fatal to the impact theory of the origin of those peaks and at the same time in full and complete harmony with the hypothesis of the volcanic upbuilding of those peaks?

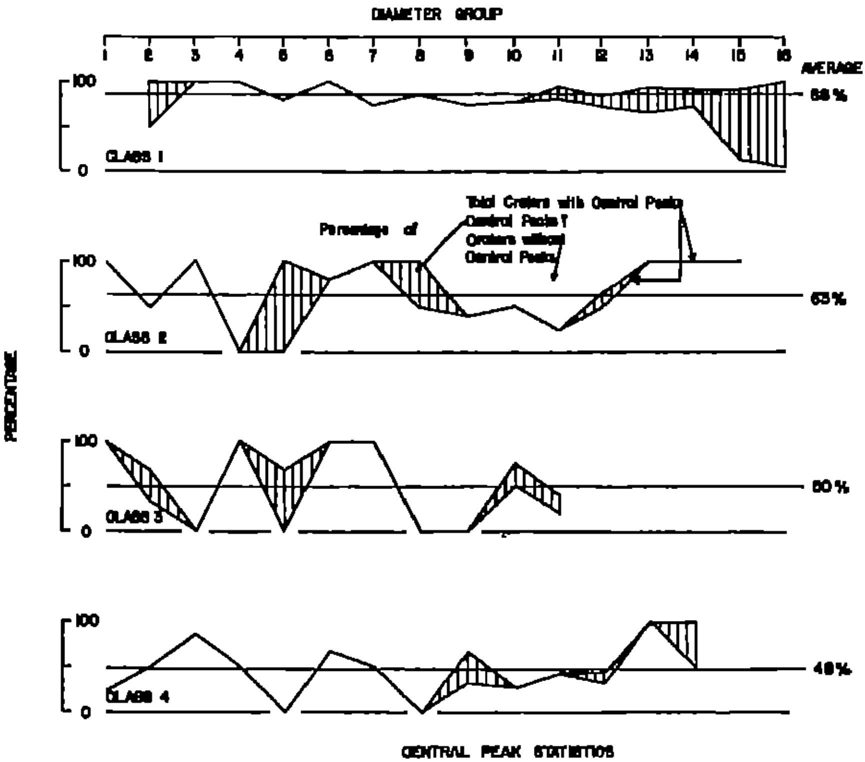


FIG 21 —Relationship between percentages of craters with and without central peaks as a function of crater diameter Data given for each class of crater

This is the quick and obvious conclusion and yet a little thought will indicate that it is not necessarily the correct one In the case of Timocharis the central peak crater is one tenth as broad as the main pit It actually has almost completely eliminated the peak How can a distinction be made between the listed cases in which the crater is smaller than the central peak and the succeeding types represented by Zagut and Cassini in which a crater lies where a central peak ought to be? What is the volcan

ic force which built the majority of peaks which do not show summit craterlets?

The area of the 59 per cent of the moon s surface which is visible to us is nearly three times that of the United States or 8 600 000 square miles It has been estimated by numerous observers that the total number of lunar craters which can be seen in large telescopes is between 200 000 and 1,000 000 almost all of which are extremely tiny If the lower limit is selected, we find about one crater for every 40 square miles In Table 4 are 177 craters which are large enough to show central mountains. As these data are not complete it may be that among the larger craters on the moon the

TABLE 13

CRATERS WITH SMALL CENTRAL PEAK CRATERPITS

Name	Diameter Central Peak Craterpit (feet)
Timocharis	11 500
Plinius	9 500
Herschel	9 500
Landsberg	6 000
Capella	5 000
Bürg	4 000
Albategnius	3 500
Alpetragius	3 500
Pitatus	3 500
Piccolomini	3 000
Arzachel	3 000
Kant	2 500

total is 200 Some of these mountain masses are at least 10 miles across 2 miles in diameter may be a representative figure for the size of the average summit—an area of 3 square miles On this assumption there is a total area of $200 \times 3 = 600$ square miles of central peak summits This leads to the conclusion that with the small craters distributed essentially at random as they seem to be there should be 15 craters which have central peaks with summit craters purely as a result of the chance distribution of the small craters

So far 12 such craters are known The agreement is excellent The case for the meteoritic nature of the lunar craters is even more solidly founded and the volcanic hypothesis is correspondingly weakened

While there is no known lunar mountain which closely resembles a vol

canic cone, there are numerous domes which appear like small terrestrial shield volcanoes One lying between Mercator and Kies, is 2,000 feet high and 9 miles broad The mean angle of the outer slope is 4°8 It is even flat ter, therefore than Mauna Loa, whose slope averages 5°1 There is a sum mit crater about 4 000 feet in diameter Similar objects are found scattered over the surface One which has a crater 9 000 feet in diameter lies on a long ridge 130 miles east of Lalande another is south of Mairan still an other is south of Herodotus Eight are found between Copernicus and Kepler while a group is suspected northwest of Marius Two lie near Arago

In most of these formations there are small central craters or crater like formations Pickering (74) has identified them as true volcanoes If this is correct they probably were of the effusive type rather than explosive as they do resemble terrestrial volcanoes of that nature Marshall (29) has proclaimed them to be the surface expressions of buried laccoliths calling them craters which did not complete the hypothetical developmental se- quence first advanced by Tomkins (28)

It is possible that neither explanation is correct It is strange but none of these mounds is found in the bright uplands all of them are located on the lava flows Their nature is less clearly understood than are the other surface details

The majority of the lunar craters can be divided into four classes on the basis of relative apparent age In each class but primarily in Class 1 the freshest appearing craters numerous correlations can be set up with re- spect to the pit dimensions and appearance The craters of the moon fulfil every logical extrapolation of the known explosion pits and the terrestrial meteoritic craters and cannot be correlated successfully with any known form of vulcanism

The case for the explosive origin of the moon s craters is unassailable. The probability is very great that the explosions were caused by the im pact and sudden halting of large meteorites

CHAPTER 8

Evaluation

IN THE preceding chapters is a mass of data concerning lunar craters as individuals and as members of well-defined sequences The correlations and relationships derived appear to be conclusive in identifying the craters with explosion pits The pits were dug with single applications of energy These energies were not derived from any form of vulcanism comparable to those found on earth The magnitude of the energies involved far transcends that of any explosion recorded in terrestrial volcanic processes or of any man made explosion There is only one process known to be capable of releasing the necessary energies close beneath the lunar surface This mechanism is the impact and sudden halting of large meteorites Almost every observed condition of the lunar crust may be completely explained by the meteoritic theory or associated subsequent processes The exceptions are the very few formations obviously due to a mild igneous action This seems as close to a certainty as any such theory can be when it is derived from a distance

In reaching this conclusion nothing has been said regarding the sizes of the meteorites which produced the craters on the moon Wylie (40) has calculated that the mass which blasted out the great crater in Arizona was between 30 and 64 feet in diameter If the meteorite were spherical and 50 feet in diameter the volume of material dug out of the ground and deposited in the rim was sixty thousand times larger than the volume of the meteorite The accuracy with which this ratio is known is not high but the correct order is indicated

To a fair approximation the volume displaced by a meteorite striking the moon will be in the same ratio to the meteoritic diameter Table 7 gives the volumes of the subsurface portions of typical lunar craters Column 3 of Table 14 lists the diameters of nickel iron meteorites which could produce craters of the suggested sizes on this constant volume ratio assumption In column 4 are listed the calculated meteoritic diameters as derived by the energy extrapolation method of Appendix D

The diameters are probably correct, for average cases within a factor of less than 3 A rapidly moving meteorite will make a larger crater than an equal mass moving more slowly and a shallow explosion, such as would come from a meteorite striking at a large angle from the vertical will give a smaller crater than a deeper blast unless the depth of the latter explosion is excessive

The resulting dimensions for the meteorites which have formed the lunar craters are rather surprisingly small Even the largest crater of the normal group Clavius, is probably the son of a parent about 1 or 2 miles in diameter

The calculated meteoritic diameters bring forcibly to mind such names as Apollo Hermes Amor Adonis and Albert names of tiny asteroids

TABLE 14

SIZES OF CRATER PRODUCING METEORITES

(1) Crater Diameter (Miles)	(2) Crater Volume (Cubic Miles)	(3) Meteorite Diameter (Feet)	(4) Meteorite Diameter (Feet)
0 1	7×10^{-6}	7	4
1	3×10^{-3}	51	39
20	92	750	900
40	615	1 400	2 100
60	1 850	2 100	3 200
80	4 050	2 700	3 800

which in recent years have paid fleeting visits to our neighborhood tiny asteroids each of which could, in some future year, entirely devastate an American state or a European country tiny asteroids which might wipe out local species of flora and fauna Sudden disappearances of long established groups of contemporary life have been recorded in past geologic history Is it not possible that the causes of these occurrences were meteoritic impacts?

If the craters of the moon were formed by the infalls of meteoritic bodies they should be distributed essentially at random over the lunar surface In the bright uplands this condition is fulfilled if the rare chain craters are omitted The frequency of craters, large and small is high and the pits are found almost uniformly scattered Similarly the distribution of craters on the dark maria is random but the crater density is

many times lower than in the brighter sections At first glance this might seem to militate against the impact theory but, while the discrepancy in visible craters is real, the explanation is simple

The great lava sheets with few exceptions, spread outward from Mare Imbrium In so flowing they covered a vast area of the lunar crust whose nature was very similar to the rough south polar zone Thousands of ancient craters were swallowed up in the deluge and are marked now only by the highest portions of their rims extending above the frozen surface As might be expected the farther the lava flowed the thinner became the sheet In Oceanus Procellarum there are few drowned crater rims visible except near the edges of the flow In northern Mare Nubium the same is true but south of a line from Grimaldi to the Sinus Medii the shallower lava allows great numbers of craters to project It is probable that beneath the dark matter of the maria lie craters in profusion equal to that of the southern uplands The two modes of crater distribution upland and sea thus mark a temporal rather than an areal distribution The maria were formed after more than 90 per cent of the craters appeared The remaining few per cent scattered in random fashion over the entire surface

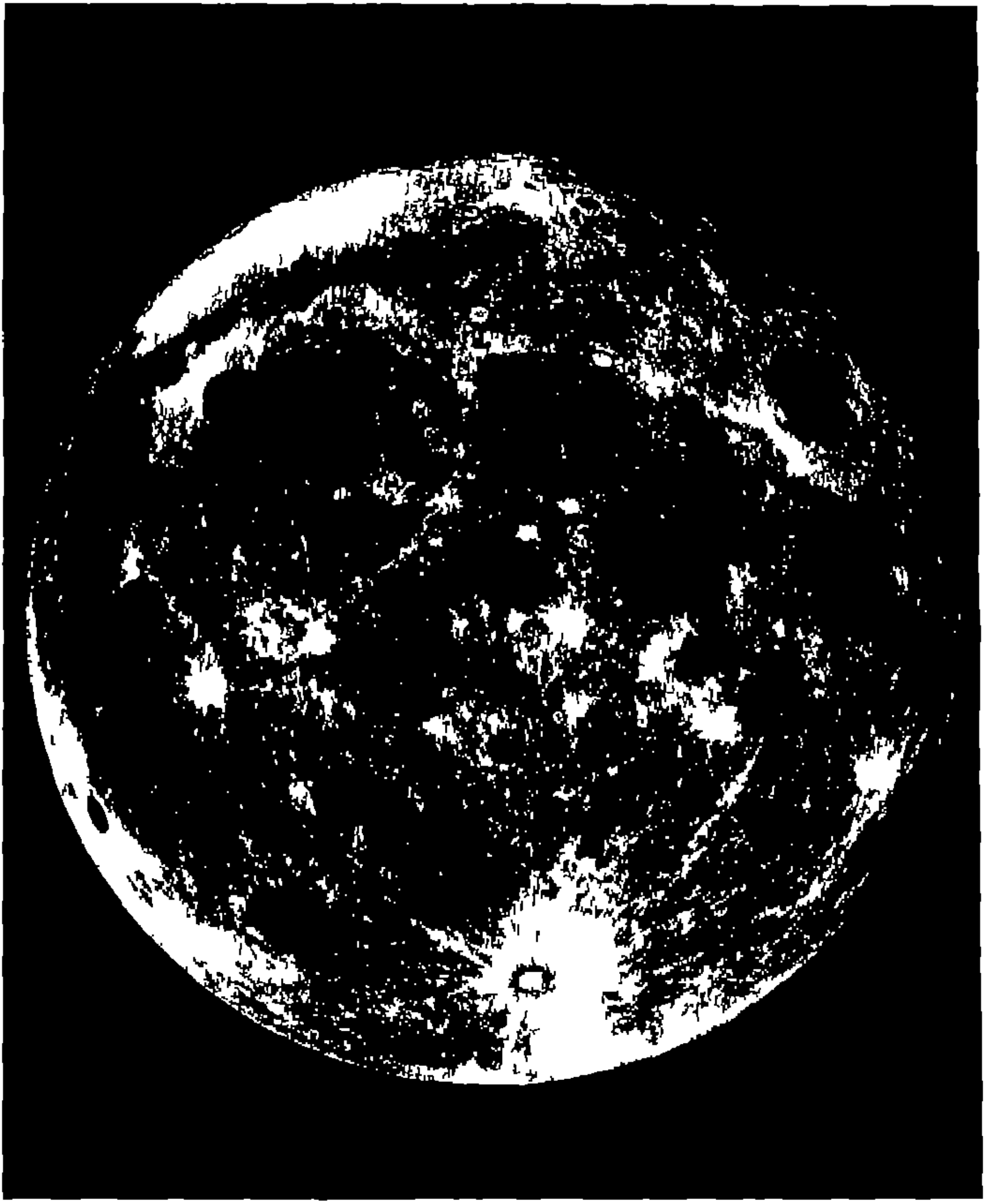
This conclusion is subject to two additional checks In Table 4 329 craters were arbitrarily divided into four classes Those craters placed in Class 1 were adjudged to be the sharpest and cleanest in appearance and hence presumably were the last to be formed Classes 2 and 3 were reserved for craters which appeared progressively older and more dilapidated Class 4 contained the lava filled craters

The four lunar quadrants 1 2 3 and 4 are respectively the NW NE SE and SW quarters Quadrants 1 2 and 3 have large lava flows 4 has relatively little lava. In the following order 4 3 1 and 2 the quadrants show increasing areas affected by lava

It is probable that the craters listed in each class in Table 4 are representative samples although the Class 1 craters have been given too much weight unjustifiably on a statistical basis

If as seems likely the Class 1 craters are the newest they should appear about as frequently on the maria as elsewhere and hence should be equally abundant in all four quadrants The Class 4 craters should be found mainly in the first three quadrants although a line of them in the fourth quadrant is near the central meridian Craters of Classes 2 and 3

PLATE XIII



DISTRIBUTION OF PREMARE LUNAR CRATERS WHICH HAVE BEEN PARTIALLY DROWNED BY THE GREAT LAVA FLOWS MOON AGE 14 9 DAYS, MARCH 8, 1936 (LICK OBSERVATORY)

are older and hence should be concentrated in the third and particularly in the fourth quadrants Table 15 lists the actual distribution of the 329 craters As may be seen, the expected distribution is closely approximated

It has previously been noticed that the craters which show rays are usually new appearing and hence the majority is in Class 1 In Table 16 are the names of the principal ray craters These ray systems are distributed in the four quadrants as summarized in Table 17 Within the statistical limitations imposed by the small sample the distribution of ray craters is essentially the same as that of the Class 1 craters and is random over the entire lunar disk

From these summations it is evident that the grouping of the craters into the four classes is primarily an age classification The random

TABLE 15

DISTRIBUTION OF CRATERS BY QUADRANTS

Class	Quadrant			
	1	2	3	4
1	44	55	53	41
2	4	4	11	24
3	0	0	12	15
4	16	14	21	15

scattering of the postmare craters is clearly indicated, and all observations of the premare craters suggest that they too were formed in equal abundance in the four quadrants

On earth the volcanic areas are confined to long, narrow zones Active regions are often found along great fissures such as the Hawaiian Islands volcanoes and the Javanese and Sumatran string of volcanoes Conditions are quite different on the moon and yet even there attempts have been made to associate craters which happen to be nearly lined up Daly (28) has pointed out what he believes to be a fissure chain consisting of Pontecoulant, Frauenhofer Furnerius Petavius, Vendelinus, Langrenus, Webb, Apollonius Mare Crisium, Cleomedes, Bernouilli, Messala and Schumacher Similarly, other groups have been connected One such is Catherina, Cyrillus, and Theophilus another is Albategnius and Hipparchus A prominent line contains Walter, Regiomontanus Purbach,

Arzachel Alphonsus, and Ptolemaeus Near the east limb Grimaldi, Hevel and Cavalerius are sometimes associated

Three striking facts are immediately apparent Each "chain is composed of craters of widely different ages Each "chain is parallel to a meridian and hence parallel to the near by terminator Craters appear prominently only when near the terminator

TABLE 16

PRINCIPAL RAY CRATERS

Quadrant	Name	Quadrant	Name	Quadrant	Name
1	Agrippa	4	Furnerius A	4	Messier A
4	Alfraganus	2	Gambart A	3	Mösting A
2	Anaxagoras	1	Geminus	3	Mösting C
1	S of Apollonius	1	Godin	1	SW of Newcomb
2	Aristarchus	4	Hind C	2	Olbers
1	Aristillus	4	E of Janssen	1	Proclus
1	Autolycus	2	Kepler	2	Pytheas
3	N of Bailly	3	Lalande	4	Stevinus A
2	Bode	3	Landsberg A	1	Strabo
3	Byrgius	4	Langrenus	1	Taquet
3	Campanus	1	Littrow	1	Taruntius
4	Censorinus	3	Lubiniesky B	4	Theophilus
1	Cleomedes A	3	Lubiniesky C	2	Timaeus
2	Copernicus	4	Mädler	2	Timocharis
3	Crüger	1	Manilius	1	NW of Triesnecker
1	Dionysius	2	Marco Polo	3	Tycho
3	Euclides	2	W of T Mayer	4	Vega
1	Eudoxus A	1	Menelaus	4	Vendelinus B
2	Euler	3	Mersenius	3	Zuchius
4	Faye	3	Mersenius C		

TABLE 17

DISTRIBUTION OF RAY CRATERS BY QUADRANTS

Quadrant	No of Ray Craters
1	18
2	13
3	15
4	13

As a result the shadows force spurious groupings in the north south direction Close examination of photographs reveal other alignments which are equally exact Among these may be mentioned Blancanus Clavius Maginus Saussure Walter and Werner Another possibility contains Almanon Geber Abenezra and the ancient pit it overlaps Playfair and Werner A third set is Maginus, Tycho Unnamed Cichus, Mercator, and Campanus

Doubtless many other such fortuitous groupings could be found On a random distribution of craters they are to be expected Analogous and equally spurious alignments can be seen in the pattern of pellets fired from a shotgun against a target

The full moon seen through a small telescope or a pair of good binoculars looks like a peeled orange Radiating in all directions from Tycho are great white streaks, many of which reach to the limb Generally the rays lie on great circles intersecting in the central crator or its rim Never do they have an artificial look They are patchy and hazy often poorly defined Their brightness depends on the background for in the bright uplands of the south the Tychonic rays are brilliant but on the maria they are much less conspicuous With increasing distance from Tycho the rays irregularly fade out and disappear

Around Copernicus are rays of slightly different appearance They are more numerous and more irregular than those from Tycho but again the association with the main crater is clear This is also evidenced in the near by system of Kepler

These light-colored streaks are definitely surface features they are permanent and reappear without change from lunation to lunation

Some of the largest Class 1 craters show rays—Langrenus Theophilus Copernicus and Tycho for examples—but the great majority of the systems are very tiny Surrounding some of the small craters are bright patches or halos In many cases careful examination of the wonderfully clear Mount Wilson and Lick Observatory photographs shows them to be miniature ray systems quite like the larger forms in all but size A common origin is apparent

Hundreds of the baby ray formations exist on the moon and in all cases the center of the system is found to be a minute intensely white craterlet usually less than 1 mile in diameter The fan of rays around the smaller pits is usually from 20′ to 2′ in diameter and the area covered by the rays is roughly proportional to the area of the central crater

Pease with the 100-inch reflector noted that practically every white speck showing on Mount Wilson lunar photographs stands out distinctly as a craterpit with its rim above the surface and the bright rays are seen as the illuminated sides of low mounds which always cast shadows in the same direction as the neighboring craters do

In general the streaks become visible about twelve hours after sunrise and brighten for one or two days They remain visible slowly becoming

more conspicuous until full moon and disappear about twelve hours before sunset Their visibility is primarily a function of the angle between the line of sight from the earth and the direction of the light from the sun not of the angle of illumination, as at full moon the rays abound all over the disk

Buell and Stewart (126) have run laboratory experiments to verify this point They conclude that the lunar rays are streaks of dark normal material mixed with powder Naturally the pulverized fragments have settled into interstices in the scattered rocks of the moon's crust

The changing visibility of the rays is in agreement with this conclusion If there is much pulverized material mixed with the less finely divided particles the former would settle into the lowest depressions. Analysis of light reflected from the moon has indicated that it possesses an extremely rough surface This irregularity acts to hide the finer material by occultation near the limb and by shadows near the terminator Under a high sun a particle hides its own shadow and hence appears to be brighter The surface is only partially covered by this white matter even in the brightest portions of the rays Therefore we see an average of the brightness of the ray material and the darkness of the background As the maria are darker than the uplands the rays should and do fade on entering the lava flows

Like the craters the rays have had their full share of proposed origins They usually are dismissed with the explanation that they are composed of volcanic dust from the eruptions which supposedly formed the main craters Some authors have postulated an atmosphere in which winds spread the ash Others more realistically dispensed with an atmosphere and depended on the low surface gravity to permit the ash to spread widely even with moderate velocities of eruption The circular velocity at the moon s surface is only 1 04 miles per second

Tomkins who first proposed the laccolithic theory of crater origin devised a saline efflorescence theory (76) to account for the rays In northern India lies the Salt Range which is known to be volcanic From it run three streamers where the upward movement of water under a hot sun has led to evaporation and the deposition of salts One of the streamers runs south to the sea one goes west over the Frontier Province and probably across Persia as far as Lake Van and the third follows the watershed of the Ganges and Jumna rivers for over 800 miles Similar markings are known in other deserts in Asia and in the Libyan Desert

Other than the fact that light-colored streaks have been formed on

PLATE XIV

RAYS AROUND BOMB CRATERS, REGENSBURG GERMANY (OFFICIAL PHOTOGRAPH U S AIR FORCES)

earth by this process nothing is known which would associate such markings with the lunar rays The salt zones are not appendages of any crater, volcanic or otherwise

Nasmyth and Carpenter (77) felt that the shattering of the lunar globe around focal points (craters) was the origin of the rays We now know that such a mechanism is physically impossible as it implies far greater rigidity than the crust of the moon can possess The emission of lavas from the cracks was supposed to produce the actual rays A modification of this idea is that crystalline dust was emitted from surface cracks too small to be seen and deposited on both sides of each fissure Fauth (72) even suggested that the rays were made of ice crystals blown through holes in the crater walls

In previous chapters it was established that the lunar craters are great explosion pits In the terrestrial meteoritic explosion craters there is always a great deal of rock flour, pulverized sand and rock Barringer (78) estimated that fifty million tons of it were thrown out of the Arizona crater, one-sixth of the total mass ejected On the airless moon, with its low surface gravity much of this powder would have been available to form rays It is well known that powdered rock is almost always whiter than the original solid

If the rays were formed by matter thrown from the central craters the projection on the surface of the trajectories would be great circles Almost all the rays fulfil this requirement The principal exception is the great ray from Copernicus passing across Mare Imbrium just east of Timocharis This ray projected southward, would miss the near wall of Copernicus by 40 miles Nevertheless it is positive that the ray came from Copernicus as it is the blend of many smaller patches, every one of which points directly to the main crater A narrow stream of water from a hose in which both the altitude and azimuth of projection are changed rapidly will give a comparable series of splashes on a pavement

Probably the nearest terrestrial counterpart to a lunar ray patch is found when a cake of dried mud drops from a speeding car and shatters into dust on a dark asphalt road In Pitatus markings of this type are very clearly shown They have come from Tycho

Confirming the observations of Pease at the telescope and Buell and Stewart in the laboratory that the rays contain dark as well as light matter it is noted that along many of the larger rays from Tycho and in

particular, Copernicus, there is a definite preference of small craters for the regions covered by the rays. Many of these "on the ray" craters are elongated and point roughly to the main crater. This is best shown southwest of Copernicus. Clearly, much solid matter was ejected along with the rock flour at the birth of the central crater, and some of the larger masses dug elongated craters on impact. Slowly moving bodies could do this, while blows from faster moving masses would give circular pits.

The fact that finely divided rock can produce long rays is evidence that no appreciable resisting medium surrounds the moon. If an atmosphere were present at the time of the explosion, the dust would be deposited around the crater in nearly uniform fashion unless winds caused a systematic shift in position.

The great ray systems are all from relatively new craters. Older pits do not show such appendages. Two reasons for this may be advanced. The rock flour would be deposited mainly in the lowest places. Thus it would be the first to be covered and hidden by any flying debris scattered from other later crater births. It is also possible that the older craters were created during a period when the moon still had a residual atmosphere which prevented the development of rays or obliterated them. Perhaps both explanations are correct.

In view of the conditions on the moon as we know them, the observed characteristics of the lunar rays are entirely consistent with a meteoritic origin for the craters.

CHAPTER 9

The Lunar Atmosphere

DOES the moon have an atmosphere? We do not know No single observation has yet been made to prove either the presence or the complete absence of air on the moon Much information on limiting con ditions can be obtained by indirect methods and analyses but far more delicate tests must be devised to ascertain correctly the true lunar conditions

The most promising approach is to determine the nature of the earth's atmosphere first and then to reason from these data just what atmospheric conditions could obtain on the moon

The atmosphere of the earth is divided into three major layers The lowest or troposphere extends upward for perhaps 8 miles It is a region of great changes seasonal and irregular daily and local It can be investi gated directly by hundreds of weather stations distributed all over the earth by airplane and radiosonde balloon Above it lies the stratosphere rising to about 30 miles Above this lies the ionosphere Meteorological rockets have been sent into the higher atmosphere so that direct measures could be made on the nature of those regions measures which were possible only by indirect methods previously

Before 1923 the standard atmosphere postulated a rather rapid fall off in density with increasing height In that year the pioneering studies made by Lindemann and Dobson (79) on meteors startled meteorologists by proving that the density of the earth s upper air was far higher than had been assumed

In 1931 F J W Whipple (80) and Duckert (81) independently showed that there were anomalous reflections of the sounds of gunfire from layers in the air about 35 miles up These observations led to the conclusion that there was a decided rise in temperature to a maximum at that height. The best figure for this temperature peak is 365 K Two years previously

Taylor (82) had anticipated their conclusion by predicting from theoretical considerations that such a maximum should exist Pekeris (83) later amplified and extended Taylor's calculations Pekeris also showed that the temperature must again fall immediately above the high temperature zone It had been observed from barometric measures and confirmed by the velocities of sound waves observed at great distances from the violent explosions of the Siberian meteorite of 1908 and the volcano Krakatau in 1883 (84) that there are two natural periods of oscillation of the atmosphere (12^h and 10^h5) which require that there be a low temperature region about 50 miles high

Humphreys (85) has demonstrated that ice crystals can be formed over ice at a temperature of 160° K From this he suggested that the noctilucent clouds which appear in a narrow range of altitude centered near 51 miles are (86, 87), in fact, ice crystals, and thus there is agreement with the fall in temperature deduced by Pekeris

There is additional evidence of a peculiarity near the 51 mile level for it is at that point that the greatest frequency of meteor trails or phosphorescent wakes occurs Many times bright meteors penetrate well below this level but leave trains only along the small portion of their paths through this region

The aurora polaris is not only beautiful it is useful Several pertinent facts have been derived from its study Auroral light is definitely an upper atmospheric phenomenon A low density is required to permit the auroral discharge The lower limit of observed aurorae varies from 53 to 106 miles (88) There are two well-defined maximums of intensity and occurrence at 62 and 66 miles while the upper limit changes on different occasions from 62 to over 180 miles

In contrast to the brilliant and well marked auroral phenomena, there is a different type very diffuse which has been observed up to about 600 miles Aurorae over 250 miles high seem to occur only in sunlight

At one jump the atmosphere has been found to extend upward to a height of at least one-seventh the radius of the earth and even this extreme figure does not mark the limit Even here the density is high enough to allow frequent collisions with electrons or alpha particles from the sun

Most of the spectral features of aurorae arise from O_2 and N_2 molecules, none is found from hydrogen either molecular or atomic The tremendous

green auroral line, λ 5577, is due to atomic oxygen. It is obvious that in the regions where the strong and definite auroral arches and streamers are found there has not been a great deal of separation of molecules and atoms according to mass. While it is possible that the upper reaches of the air contain only hydrogen and helium, that condition does not obtain up to at least 200 miles and to perhaps 600 miles, although the percentage of the light gases may be considerably higher than at the surface.

Vegard (89) analyzed the distribution of energy he observed in the nitrogen bands of the auroral spectrum and derived a temperature of 218° K. at a height of about 69 miles. This implies a moderate increase of temperature above the 51-mile minimum. Rosseland and Steensholt (90) have corrected this value to 347° K. and thus have shown that there is a marked rise in temperature in the main auroral zone.

F. L. Whipple (91) has derived a curve relating height to atmospheric density from photographic observations of the rate of deceleration of meteors. Two cameras are used, one located at Cambridge and the other at the Oak Ridge station of Harvard Observatory, 23.5 miles distant. When a meteor is photographed simultaneously by the two cameras, the spatial position of any point on the trajectory can be determined with great precision by trigonometric methods. A rotating shutter operated by a synchronous motor interrupts the exposure at intervals of $0^{s}.05$, causing the trail to appear as a broken line. These reference points allow a determination, first, of the angular velocity; then, the linear velocity; and, hence, the deceleration, which is usually small, of the order of 1 mile per second per second. In conjunction with the mass of the meteorite derived from its magnitude, the density of the air may be computed. Table 18 lists the adopted temperature data and Whipple's derived density distribution. The seasonal effect is to raise the upper atmosphere in summer and to lower it in winter, a total range of roughly 3 miles. Whipple indicates that he is not thoroughly satisfied with the temperature data. The pressures and temperatures in the lower reaches have been checked by instruments carried in V-2 rockets fired in New Mexico (120).

The numbers of small meteorites which strike the earth's atmosphere are far greater than the relatively few large masses. This is a fortunate distribution as the air is only a partial protection. On the average, meteoritic masses greater than ten pounds and less than perhaps a few tons will slow up to a free fall before they are entirely vaporized and will then drop

dark stones Of the myriads of smaller masses nothing but dust reaches the ground Larger bodies will strike the ground still glowing or will explode to form craters The latter are very frequent on a geologic time scale extremely rare on a human time scale To all intents and purposes then the air acts as a rather effective shield against interplanetary artillery

Studies by Whipple (91) and Öpik (92) show clearly that the sporadic meteors appear at a height of about 60 miles regardless of their apparent magnitude. Öpik has suggested that shower meteors begin higher near

TABLE 18

ADOPTED ATMOSPHERIC CONDITIONS

HEIGHT		T (°K)	−LOG ρ*
Km	MI		
20	12 4	219	4 06
25	15 5	220	4 40
30	18 6	223	4 74
35	21 7	256	5 12
40	24 9	299	5 45
45	28 0	322	5 73
50	31 1	340	5 97
55	34 2	356	6 21
60	37 3	365	6 42
65	40 4	355	6 62
70	43 5	309	6 78
75	46 6	230	6 93
80	49 7	184	7 19
85	52 8	186	7 48
90	55 9	206	7 78
95	59 0	233	8 07
100	62 1	266	8 37
105	65 2	303	8 67
110	68 4	347	8 96
115	71 5	393	9 26
120	74 6	440	9 55

* ρ expressed in grams per cubic centimeter

70 miles Whipple s photographic survey yields similar heights However the end points of the trails of sporadic meteorites are strongly related to the brightness of the meteors the brighter objects penetrate deeper into the atmosphere At +4 mag (corrected to 100 km high in the zenith) the average end height is about 50 miles At −4 mag the corresponding figure is about 38 miles Shower meteors seem to disappear at a height near 56 miles Superimposed on these average distributions of height is another factor The lower velocity meteors appear and disappear at lower heights than do the high velocity objects At 45 miles per second the mean

height (average of the two end points) is about 59 miles If the velocity is 8 miles per second the mean height is only 34 miles

These heights may be converted into air density units or since they are easier to handle logarithmic densities

Early astronomers soon realized that, even if the mass of the lunar air were proportional to that of the earth the surface density would be much less Observations of occultations of different stars show that the horizontal refraction of starlight at the moon s limb does not exceed 2″ of arc and is probably much smaller If the surface density of the lunar air were equal to that of the earth, the horizontal refraction would be 2 000″, which must be doubled for the case of an occultation as the starlight must penetrate the entire thickness of air twice From these data the maximum allowable

TABLE 19

LOGARITHMIC AIR DENSITIES AT POINTS ON METEOR TRAILS

	Appearance	Mean	Disappearance
Bright sporadic meteors	−8 07		−6 48
Faint sporadic meteors	−8 07		−7 30
Shower meteors	−9 24		−7 78
Fast meteors		−8 07	
Slow meteors		−6 19	

density of air at the moon s surface is only 1/2 000 that of sea level density on earth

Russell, Dugan and Stewart (93) estimate that the density probably is not greater than 1/100 000 that of the earth s air If the lunar mantle were as dense as 1/10 000 the twilight zone illuminated by the full sun would be more conspicuous than the dark part of the moon lighted by the full earth

The latest and most important effort to detect a lunar atmosphere was made by Lessenkoff (94) He failed but succeeded in proving that the upper limit of density is far lower than has been previously suggested

Fessenkoff [95] examined with a piece of polaroid filter the faintly luminous area near the center of the moon on the dark side of the terminator at first and last quarters The surface brightness of this area is considerable and the test for polarization by rotating the polaroid presents no great difficulty Fessenkoff found no change in the surface brightness as the polaroid was turned and he concludes—presumably on the basis of laboratory tests—that the ratio of the brightness at radial and at tangential orientations of the axis of the polaroid cannot be in excess of $n = 1\ 04$

If the diffuse light which Fessenkoff observed had been produced in its entirety by "twilight" in the lunar atmosphere the polarization should have been complete, because the phase angle at first and at last quarters is 90° But the light is mostly caused by scattering in the earth's atmosphere—that is by an ordinary lunar halo, and perhaps by a small amount of the earth-lit surface of the moon This background illumination should be almost completely unpolarized If we designate this back

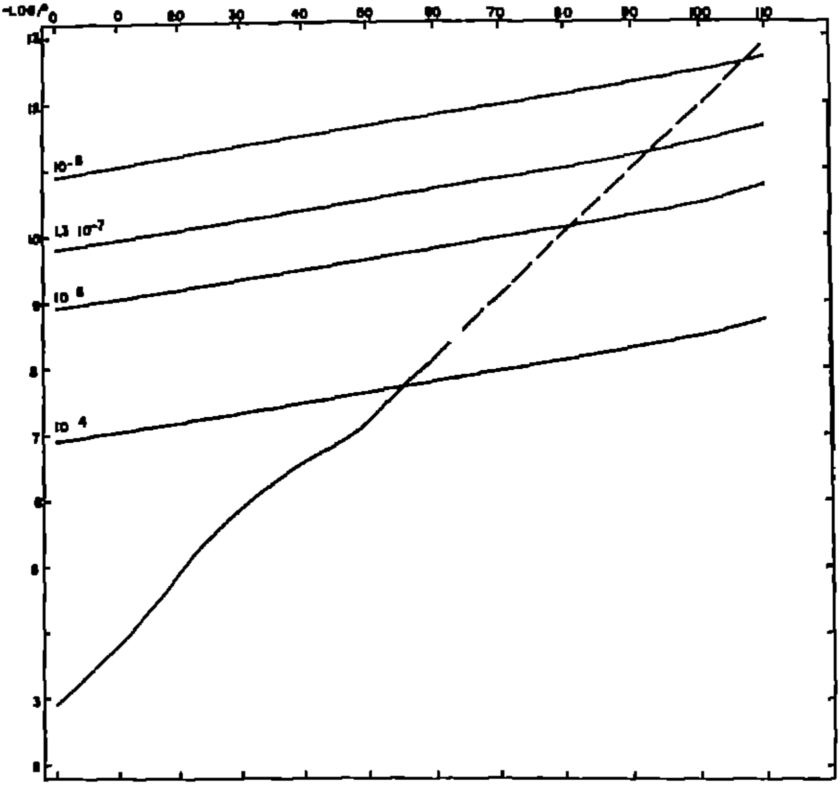


FIG 22.—Relationships between height and logarithmic air densities for the earth and moon Four assumed density ratios are shown for the moon

ground surface brightness as b and the hypothetical polarized light of the lunar twilight as c we have

$$n = \frac{\frac{1}{2}b + c}{\frac{1}{2}b} \quad \text{or} \quad \frac{c}{b} = \frac{1}{2}(n - 1) \tag{10}$$

If L is the amount of solar radiation received by a unit of surface on the moon oriented at right angles to the radiation ρ is the density of the lunar atmosphere and μ is the coefficient of scattering then the surface brightness of an element of the moon located on the dark side of the terminator is

$$\mu L \rho \, dh \tag{11}$$

Integrating this over the entire thickness of the lunar atmosphere and designating by m the mass of a vertical column of unit cross-section, we find that

$$\mu L m = \tfrac{1}{2}(n-1)\, b\,. \tag{12}$$

The quantity b was determined by Fessenkoff in the following manner. He measured the surface brightness of the sky in the vicinity of the sun and found it to be twice that of a standard plane white surface illuminated by the sun. He next computed the ratio between the surface brightness of the solar halo and that produced by a source whose stellar magnitude is 14.17 mag. fainter than the sun but which has a similar distribution of light over its surface. He then computed the difference arising from the facts that the lunar observations were made near the terminator and the moon was at first or at last quarter. Since the surface brightness of the solar halo in terms of the brightness of the standard surface depends upon the scattering power of air and upon the mass of the terrestrial atmosphere, he obtains an expression for b which involves this mass, M. It is assumed that the coefficients of scattering, per unit mass, in the atmosphere of the moon, μ, and in the atmosphere of the earth, μ_1, are the same. The final result is an expression for the ratio of the two masses

$$\frac{m}{M} = 0.196 \times 10^{-4}(n-1)\,. \tag{13}$$

From the observations, $n - 1 < 0.04$. Hence,

$$\frac{m}{M} < 10^{-6}\,. \tag{14}$$

The numerical maximum limit derived from the above figures is 0.784×10^{-6}. As the surface gravity of the moon is only one-sixth that of the earth, the lunar atmosphere will extend higher in inverse proportion. The density of the lunar atmosphere relative to that of the earth is directly proportional to the ratio of the air masses times the ratio of the surface gravities. Therefore, as an upper limit,

$$\frac{\rho_m}{\rho_e} = 1.3 \times 10^{-7}\,. \tag{15}$$

If the earth's atmosphere were compressed to standard conditions throughout, it would make a layer 4.965 miles high. Similarly, the lunar atmosphere would make a layer covering the moon to a depth of not more than 0.25 inches. In more everyday terms, the earth's atmosphere, compressed to the density of steel, would be a protecting armor 49 inches thick, while the lunar mantle would be less than 1/200 the thickness of the finest commercial gold leaf.

In spite of having been searched for many times, aurorae have never been observed in the lunar atmosphere. Consequently, it is certain that

neither oxygen nor nitrogen is present in the lunar atmosphere to partial densities comparable to those which are observed in the earth s atmosphere between 53 miles and some height over 180 miles The total density range whose upper limit defines the maximum permissible density of oxygen or nitrogen in a lunar air is $2\ 5\times10^{-4}$ to at least (extrapolated) 10^{-17} times standard air density This latter figure is based on the failure to see strong lunar aurorae It may well be that faint aurorae would escape notice and hence the density of oxygen or nitrogen may be somewhat higher than 10^{-17} but not above $1\ 3\times10^{-7}$

As the various types of observations are made more and more accurately, the maximum possible density of the lunar air becomes lower and lower Even so unless the air is entirely absent there will exist a critical height at which the lunar atmosphere will equal the terrestrial air in density for whatever value of lunar surface density there may be This is brought about by the lower surface gravity of the moon and the resulting low-density gradient in its air

We do not know what temperatures to expect in the lunar atmosphere, but in all probability the temperature is quite similar to that found in the earth s upper air

On a straight proportionality the lunar atmosphere would be equal to the terrestrial atmosphere in density at 81 miles if the ratio of surface densities were 10^{-4} The corresponding height would be about 93 miles for a density ratio of $1\ 3\times10^{-7}$ and 107 miles for a density ratio of 10^{-8}

These results allow a determination of the appearance and disappearance heights of lunar meteors It is assumed that the lunar meteors appear and vanish at the same air densities as those observed on earth and reported in Table 19

If for comparison purposes the density ratio is assumed to be 10^{-4} seven hundred times denser than observations allow then the bright sporadic meteors -4 mag on earth would appear at 76 miles and would strike the moon before burning out The faint sporadic meteors $+4$ mag would appear near the same height but would burn out about 26 miles high Shower meteors would flare at a height of perhaps 140 miles and would disappear at about 58 miles Fast meteors would glow brilliantly slower bodies would reach the moon with a not much reduced velocity and would still be able to do a great deal of damage Meteors brighter than -1 mag would reach the surface of the moon According to Wat

son (13) there are about three hundred thousand of this equivalent mass or greater striking the atmosphere of the earth each day As the surface areas of the earth and moon are in the ratio of 13 4 1 about twenty two thousand small and large masses ¼ gm and more, would strike the crust of the moon daily The very large majority of these would have their velocities greatly reduced Hence even a denser air than can be allowed would not completely protect the moon against the fiery rain there would be about one fall per 650 square miles per day

If the density ratio is assumed to be 1 3×10^{-7} the maximum allowable the picture is far different All the sporadic and shower meteors studied by Whipple and Öpik would penetrate the entire lunar atmosphere with out becoming luminous The atmosphere density at the moon s surface would be equal to that found 78 miles above the earth For all smaller density ratios the meteorites would strike the surface of the moon with essentially undiminished velocity

The problem can be looked at from another direction If the density of air is 1 3×10^{-7} times that of the standard atmosphere a cube of nickel iron, density eight times water, and 1 cm on a side would have to travel 31 300 miles to displace its own mass of air The distance would be over 400 000 miles if the density were 10^{-8} atmosphere For a cube of nickel iron 1 mm on a side the corresponding distances would be one-tenth as great If the mass were dust size, 1/100 mm on the side the distances reduce to 31 miles and 400 miles

The masses of the three cubes are respectively 8 gm 8 mg and 8×10^{-6} mg A mass of 8 gm on the average yields a meteor of -4 mag in the earth s air This body would penetrate the moon s air at any allowable density The 8 mg mass would yield a (terrestrial) meteor of $+4$ mag This body would also reach the moon s surface possibly with a slightly reduced velocity The tiny mass would burn out unless the density were as low as 10^{-8}

The conclusion then is that about one or two meteorites strike each square mile of the moon s surface each day Most of these bodies weigh less than 1 gm and they strike with relatively low velocities The maximum possible lunar atmosphere would be an almost inappreciable protector A necessary corollary is that the moon s crust must undergo a slow but persistent meteoritic erosion

The impact of a high velocity meteorite with the moon s rocky surface

releases tremendous quantities of energy some of which should be visible from the earth as a flash of light La Paz (96) has computed on the basis of reports on the 1908 Siberian meteorite explosion that a 176-pound mass striking the moon at 30 miles per second would give an impact flare of −1 5 mag A 10-pound mass would give a flash of +1 7 mag

It is worth while to recall that these figures are based on the estimated brightness of the impact flare −21 mag at a distance of 30 miles and not on the brightness of the real explosion unless the latter actually did occur just above the ground, as was suggested in chapter 4 The pillaring of heated clouds is well known on earth Both the low air burst New Mexico atomic bomb and the three high-air burst Japanese and Bikini bombs showed identical pillaring White phosphorus bomb and shell bursts do the same thing It is clearly an atmospheric phenomenon—rapid, violent rising of superheated gases which being contained by cooler air, remain luminous for an appreciable time A column such as this should not develop on the moon Much of the heat developed would be carried away from the explosion region by radiation or by the motion of the particles moving at explosive velocities

A 240-mm shell bursting in the air in daylight makes a brilliant flash of light lasting about two-thirds of a second When seen at a distance of 600 feet at night it is blinding, far brighter than the moon, and not much inferior to the sun Another 240-mm shell with a delay action fuze, bursting several feet below ground can be seen only by the dust and smoke it generates in the daytime At night there is a dull glow lasting less than a second The coruscating glare of the air burst is hidden beneath a canopy of dust The difference may be as much as 10–15 mag Similar phenomena are noticed at two-thousand pound bomb explosions The glow from a subterranean burst is of different caliber than that of the flash of the air burst and is at least 10 mag fainter The deeper the explosion in the ground the fainter is the escaping light.

The fifth atomic bomb, detonated at an unknown but shallow depth below the surface of the water of Bikini lagoon did not produce a brilliant flash Observers stated that the bomb possibly caused the watery blossom to glow a dull rose color Each of the four previous air burst atomic bombs was so bright that protective glasses had to be worn to prevent actual damage to the eye The brilliance was many times that of the sun A decrease of the order of 25 mag is indicated

A meteorite necessarily penetrates several of its own diameters into rock layers before exploding and thus ejects something of the order of sixty thousand times its own volume in making the crater Much of this material is pulverized and is highly effective in obstructing light Any flash would be of extremely short duration

It is entirely possible that even a ten-pound mass would not produce a flash on the moon bright enough to be easily visible from the earth However, let us assume that a visible flash were created What are the chances for its detection? Wylie states that about six thousand meteorites of mass ten pounds or more enter our atmosphere each year On a proportional basis there will be 448 such collisions with the moon Of these half would be on the wrong side of the moon and thus be lost. This leaves 224 per year On the average the moon is above the horizon half the time during daylight hours This leaves 112 The moon is half bright and half-dark over a long period of time, leaving 56 meteorites for the flashes would not be observed against the bright side It may also be expected that clouds will cover the sky half the time for most people This still further cuts down the available total Other factors tending to discriminate against the detection of a flash on the moon are that the moon is practically invisible for three days either side of new moon, just the phases when the dark side looks earthward the morning hours are not popularly used for observing the heavens except by professional astronomers and they are either studying some other celestial body or have their telescopes pointing toward the bright side of the moon Near the horizon the observing conditions are poor It is also true that almost no individual spends as much time as one minute looking at the moon with the unaided eye A pertinent question is involved in whether or not a person seeing a brief flash of light on the moon would believe it real, would report it if he did believe it, or would be believed if he reported it The psychological factor cannot be neglected

A ten pound meteorite striking at 20 miles per second is roughly equivalent to a two-thousand pound bomb—eleven hundred pounds of TNT Either meteorite or bomb would blast a crater approximately 48 feet wide and 15 feet deep in sand clay or gravel and proportionately smaller in rock

The chance of observing the flash of an actual impact of a meteorite and the moon is rather remote, yet do we know that such an occurrence has

never been seen? Are all the drawings, paintings and descriptions of stars within the horns of the crescent moon poetic license?

From the theoretical point of view the moon should be practically devoid of atmosphere At a given temperature all molecules in a gas will possess a Maxwellian distribution of velocities Thus a small fraction of the molecules will be moving several times more rapidly than the mean velocity The velocities vary as the square root of the absolute temperature Jeans (97) has shown that the rate of escape of atmospheres from

TABLE 20

MOLECULAR VELOCITIES

GAS	MOLECULAR VELOCITIES		MOLECULA VELOCITY DIVIDED BY VELOCITY O ESCAPE							
			Earth Surface		Earth $h=400$ Miles		Moon Surf ce		Moon $h=400$ Miles	
	(mps) 273° K.	(mps) 373° K	273° K.	373° K.	273° K	373° K	273° K	373° K	273° K	373° K
NH_3	0 393	0 460	0 056	0 066	0 059	0 069	0 267	0 313	0 313	0 366
A	0 257	0 300	037	043	039	045	175	204	205	0 239
CO	0 306	0 358	044	051	046	054	208	244	244	0 285
CO_2	0 244	0 285	035	041	037	043	166	194	194	0 227
He	0 815	0 953	117	137	123	144	554	648	649	0 759
H_2	1 142	1 336	164	192	172	201	777	909	909	1 064
Kr	0 178	0 208	026	030	027	031	121	142	142	0 166
Ne	0 363	0 424	052	061	055	064	247	288	289	0 338
N_2	0 306	0 359	044	052	046	054	208	244	244	0 286
O_2	0 286	0 335	041	048	043	051	195	228	228	0 267
O	0 403	0 472	058	068	061	071	274	321	320	0 376
H_2O	0 382	0 447	055	064	058	067	260	304	304	0 356
Xe	0 142	0 166	0 020	0 024	0 021	0 025	0 096	0 113	0 113	0 132

celestial bodies depends on the absolute temperature the velocity of escape from the body and the mass of the atom or molecule considered If the velocity of escape is four times larger than the mean molecular velocity those particular molecules will disappear from the atmosphere in about one thousand years If the velocity of escape is five times larger than the mean molecular velocity the depletion period is lengthened to 1 000 000 000 years If the factor is 6 the gas will remain essentially forever

Usually the velocity of escape as pertains to an atmosphere is computed from the surface radius Actually the escaping boundary is nebulous but is probably about 400 or more miles above the surface The velocity of

escape from the earth is 6 96 miles per second at the surface and 6 63 miles per second at an altitude of 400 miles The figures are 1 47 and 1 26 miles per second for the moon The difference is not significant when applied to the earth s atmosphere It is important in the case of the moon

The choice of the proper temperature is difficult to make In the upper reaches of the earth s air the temperature is relatively high according to Rosseland and Martyn and Pulley (115) believe that the increase con tinues to very high figures at about 180 miles A guess of 373° K seems conservative for the upper levels The atmosphere of the moon is probably of comparable temperature

In Table 20 are shown the mean velocities for numerous atoms and molecules as well as the ratios of mean velocity to velocity of escape For both earth and moon the data have been determined for both velocities of escape and for 273° K and 373° K for comparison purposes The table shows that the earth could hold all gases indefinitely except hydrogen unless the effective temperatures near the boundary are much higher than anticipated

The moon might be able to hold argon and carbon dioxide if the tem perature were below 273° K and would hold krypton unless the tempera ture were much higher than 373 K Xenon could also be held All other gases would depart rapidly from the moon If the temperature were 373 K or higher any of the following gases if ever present would be gone within one thousand years NH_3 CO He H_2 Ne N_2 O_2 O and H_2O

In the moon s early history its crust undoubtedly was very hot This would aid the escape of all gases but it might have been partially compen sated for by the release of gases from the body of the moon Meteorites whether stopped by air or not release small quantities of gas

The best that can be said for the existence of a lunar atmosphere is that none exists which is observable by present techniques and that even the maximum permissible atmosphere is a very poor shield against meteoritic bombardment

NOTE —Re p. 166 hydrogen lines recently have been reported in aurora spectra It has been suggested that this hydrogen came from the sun in the form of protons and was n t an original part of the earth s atmosphere (note added as book was printing)

CHAPTER 10

Ancient History

ONE by one the physical "constants," long believed to be invariant, are shown to be variable. Perhaps the most outstanding of these discoveries is that the length of the day, the period of time against which all clocks are regulated, is slowly increasing.

To ascertain a change in the length of the day, observations must be made on celestial objects whose motions are independent of the rotation of the earth. The most convenient bodies are the sun and the moon, particularly the latter. A decrease in the earth's rate of rotation causes apparent secular accelerations of the sun and moon. Observations of the time of passage of the sun across the equator, when the precession of the equinoxes is known, yield directly its secular acceleration. Fotheringham (98, 99) has discussed the numerous observations of ancient Greek, Babylonian, Chinese, and Egyptian astronomers in order to determine both secular accelerations. His decision was that, judging purely from observational evidence, the most probable values are $21\overset{''}{.}6/(\text{Century})^2$ for the moon and $3\overset{''}{.}0/(\text{Century})^2$ for the sun. Jeffreys (100) showed that the latter value might have to be somewhat reduced, but, even so, the values are closely limited.

The lunar theory demands a secular acceleration of the moon of $12\overset{''}{.}2/(\text{Century})^2$. The excess, about $9''/(\text{Century})^2$ is the observational fulcrum on which the lever of analysis in the brilliant hands of Darwin and Jeffreys operated to divulge so much information on the past history of the earth and moon.

This excess secular acceleration, unaccounted for by theory, implies an increase in the length of the day by one second in the last one hundred and twenty thousand years.

The source of this loss is not to be found in bodily tides, for the earth behaves as an elastic ball, nor in tidal friction in the open sea. Taylor (101), Heiskanen (102), and Jeffreys (103) determined the rate of dissipa-

tion of energy in the tides in various shallow seas over the earth and found that the agreement between the loss observed from the motions of the sun and moon and that calculated from the water velocities was indeed excellent. The friction of water against sea bottom in the partially bounded shallow seas of the earth, where the currents are tidally induced, reacting against the ocean as a whole, is sufficient to account for the observed increase in the length of the day.

A loss in the angular rate of rotation of the earth is a loss in angular momentum, yet angular momentum cannot be destroyed, but only transferred. Since the moon is the most important body in producing tides, its action on the earth results in a reacting transfer of angular momentum of rotation into the moon's angular momentum of revolution. The moon is thus gradually receding from the earth and the length of the month is slowly increasing.

This process may be reversed, mathematically, and the past history of the earth-moon system investigated. As the total amount of angular momentum in the system is constant, it can be shown that the month and the day may once have been equal at about 4.8 hours each. At that time the moon's distance would have been about 9,000 miles, essentially at Roche's limit.[1]

If the present angular momentum of the earth, P_E, is unity, its original angular momentum was 5.000. The present and original values for the moon, P_M, are 4.964 and 0.964. Tidal friction in the past has practically reversed the primal quantities. The value of P_M varies as the square root of the moon's distance from the earth, or

$$P_M = 4.964\, r^{1/2}\ . \tag{16}$$

These data give the relationships between the distance of the moon, the month, and the day but do not define the rapidity with which these changes occurred.

From various dynamical considerations Chandrasekhar (104) has calculated an age for the galaxy of about 3×10^9 years. The oldest known terrestrial uranium-bearing rocks which have been analyzed for their helium content are about 1.8×10^9 years old. These are pegmatites and are intrusive into still older rocks. The age of the earth is probably not

1. Actually, the moon could never have been closer than 11,000 miles. The corresponding month was then 6.5 hours long.

far from 2×10^9 years Recent work by Holmes (118) may even stretch this to 3×10^9 years Such a change does not affect the validity of the arguments herein presented

How the earth was born is not known How the moon was born is not known Darwin (9) carried the extrapolation backward to the point at which the month and the day were equal and then made the remarkable assumption that the moon once formed part of the earth The slowest natural free vibration of a homogeneous earth is nearly one-half the original length of the day or about two hours Darwin s hypothesis was that the solar tides, coming in resonance with the free oscillations of the earth resulted in monstrous tidal bulges one of which ultimately broke off to form the moon Jeffreys (100) found that closer agreement could be reached between the length of the day and the free vibration of the earth if the earth even then were nonhomogeneous Still later he had to abandon the theory (10) as contradicted by the facts for he found that the friction engendered in the still liquid earth would have been too great to permit the resonance tidal bulges from ever reaching the necessary heights Consequently, it is probable that the earth and moon are twin progeny born nearly in contact and at the same time, but always having been separate

In the future the moon will recede until the day and the month are again equal at forty-seven of our present days The moon will then be about 340 000 miles away This condition is not imminent for Jeffreys calculates that it will arise in the year 50 000 000 000 A D Even then the earth moon system will not be stable for solar tides will be acting provided that the earth still has liquid oceans and these tides will slowly bring the moon and earth closer together until at some time in the unimaginably distant future the moon will come within Roche s limit be shattered and will form a smaller but denser ring of fragments than that showpiece now circling Saturn

If the increase in the length of the day had been going on at the present rate in all past history it would have taken over 8×10^9 years to change the day from 4 8 hours to 24 hours This is an impossibly long time We must assume that the rate of change was more rapid in the past than at present never less rapid and also that the earth's beginning was about 2×10^9 years ago

From theoretical considerations Jeffreys (100) postulated that the loss

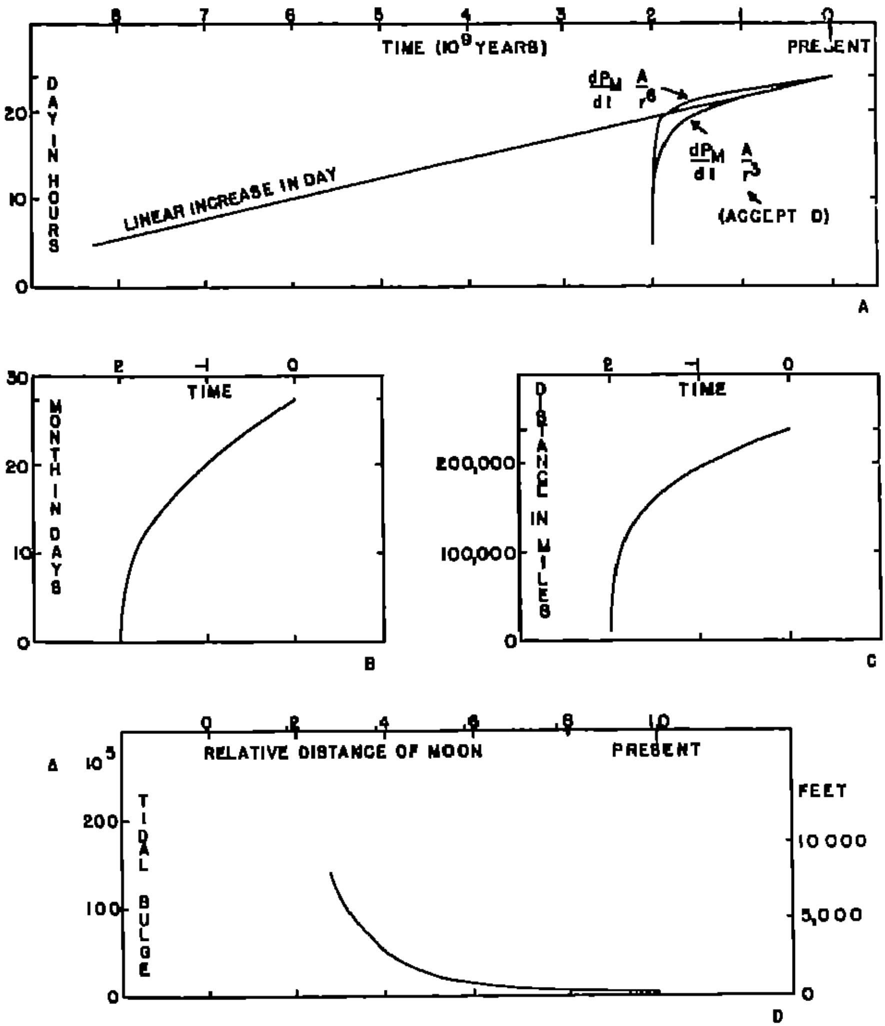


FIG 23 —Variations during geologic time (2,000,000,000 years) time unit A B C is 1 000 000 000 years. A length of the day in hours B length of the month in days C distance of the moon in miles D tidal bulge of plastic moon as a function of distance of moon from earth

of angular momentum of the earth was inversely proportional to the sixth power of the moon s distance This assumption allows a calculation of the moon s distance and the length of the day as functions of geologic time. The resulting equation[2] is

$$2\, r^{13/2} = T \qquad (17)$$

where r is the moon's distance relative to its present distance and T is the time in billions of years since 2×10^9 years ago

Probably the tidal friction in the past varied not as r^{-6} but more nearly as r^{-3} for the first assumption leads to the conclusion that the earth is

TABLE 21

DISTANCE OF THE MOON DURING GEOLOGIC TIME
(Inverse Sixth Power Law)

Distance (Miles)	Time (Unit = 10^6 Years)	Day (Hours)
50 000	08	11 1
75 000	1	13 5
100 000	7	15 6
150 000	97	19 1
200 000	631	22 0
215 000	1 008	22 8
238 840	2 000	24 0

now losing rotational speed at the rate of one second in two hundred thousand years about one-half the observed rate On the inverse cube assumption the relationship[3] between distance and geologic time becomes

$$2\, r^{7/2} = T \qquad (18)$$

The formula agrees with the observed loss of one second in one hundred and twenty thousand years (Fig 23) This equation means that the loss in angular momentum is directly proportional to the tidal force of the moon on the earth

Equation (18) probably represents the changes in the moon s distance during geologic time with a fair accuracy The moon, on any reasonable assumption, fled rapidly away from the earth in the early days Even in a conservative view it reached one-half its present distance in about 10 per cent of geologic time, and, since the Cambrian period, which began the last quarter of geologic time 5×10^8 years ago the moon has receded only

2 See Appen A. 3 See Appen A.

about 18,000 miles the month has increased by only 3 3 days, and the day has lengthened by about one hour Almost all the startling changes occurred in the first quarter of geologic time or early in the Archeozoic Era.

These wild variations in the moon's distance have caused major changes on the earth, but because the earth is so much more massive than its satellite, the effects on the moon were correspondingly greater The moon s rotational period approached the length of the month seventeen thousand times faster than did the earth s period It was thus brought to

TABLE 22

DISTANCE OF THE MOON DURING GEOLOGIC TIME
(Inverse Third Power Law)

Distance (Miles)	Time (Unit = 10^6 Years)	Day (Hours)
50 000	8	11 1
75 000	35	13 5
100 000	95	15 6
150 000	393	19 1
200 000	1 070	22 0
215 000	1 380	22 8
238 840	2 000	24 0

present the same face always toward the earth before the rotation of the latter had been appreciably affected by tidal friction

The tidal bulge of the earth averages about 4 feet, very small in com parison to the equatorial bulge The moon would possess three nearly equal axes at present if it were completely adjusted to the earth s tidal pull and its own centrifugal forces In the case of a perfect adjustment the moon would present an equipotential surface where the effective gravity is everywhere perpendicular This is the type of surface which would be formed by a liquid

Jeffreys (100) has derived convenient expressions for the semiaxes x y and z of the moon The x-axis points toward the earth the z-axis is the polar axis These expressions are respectively

$$a\left(1+\frac{35}{12}\frac{M}{m}\frac{a^3}{r^3}\right) \qquad a\left(1-\frac{10}{12}\frac{M}{m}\frac{a^3}{r^3}\right) \qquad a\left(1-\frac{25}{12}\frac{M}{m}\frac{a^3}{r^3}\right) \quad (19)$$

where a is the radius of the equivalent sphere M is the mass of the earth, m is the mass of the moon and r is the moon s distance These formulas

give increments of +125 feet, −36 feet, and −89 feet, respectively If the moon were completely adjusted to all gravitational potentials acting on it the three axes would differ from the mean by these amounts This is on the basis of a homogeneous moon If the density varies according to Wiechert s Law (116) for the earth, the above increments would be multiplied by 0 9 Fortunately, the expressions are convenient for use in calculating the tidal bulge existing on the moon at any past distance from the earth

The magnitude of the tidal bulge is a known function of the principal moments of inertia of the moon about its center Observations of the mean inclination of the moon s equator to the ecliptic (105) and also the amplitude of the moon s true libration in longitude (106) yield moments of inertia which can be explained by the assumption that the moon s tidal bulge is 2 100 feet above the mean sphere or that the semiaxis aligned with the earth is 3,140 feet greater than the average radius in the plane of the sky Such an analysis based purely on dynamical considerations can be only approximate because the accidental and systematic variations of the moon s surface particularly the division into continental areas and maria, will make the principal moments of inertia somewhat different from the case if the surface were smoother Nevertheless the discrepancy between the size of the tidal bulge found by this method and that calculated for an equipotential surface is so tremendous that it is quite apparent that the moon has not attained the theoretical equilibrium shape

Laplace was the first to notice this anomaly but was content to blame it on accidental distortions produced in the moon as it solidified Jeffreys (100) realized that it could well be that the excessive bulge was a fossil tide one formed when the moon was still plastic enough to adjust its figure to the equipotential surface At some specific distance from the earth the moon s layers solidified to the point where compensation could no longer occur and from that time on as the moon receded the primitive bulge remained as a fossil tide The strength of the lunar rocks if they at all resemble those found on earth is amply high enough to allow the moon to maintain a permanent departure from hydrostatic equilibrium This does not mean that the moon is solid all the way through Because of the low gravitational pull sufficient strength is available from the outer layers The center of the moon may still be weak

Jeffreys (100) calculates that the moon acquired a tide of the dy

namically derived height when it was at a distance 0.376 times its present distance, or at about 90,000 miles. The formulas (18), (19), and those of Appendix B (nonhomogeneous form) tell us that this distance was reached about sixty-five million years after the birth of the moon.

Somewhat later Jeffreys (107) considered the possibility that the observed moments of inertia of the moon could be explained if the form were that of a body freely rotating in 3.5 days. This assumption requires that the polar axis be much shorter than the other two. As we shall see, this is not the case.

A photograph of the moon records the apparent positions of the moon's surface markings projected against the plane of the sky. At different times the various librations show the moon to us from distinctly different directions. If the moon were exactly spherical, the apparent position of each marking could be calculated for any time. Because the moon is not spherical, but does have a large tidal bulge as well as local irregularities, the calculated positions will not agree with the observed. Such a differential will be a function of the height of a point above or below the mean sphere.

This method was employed several times to measure the departure of the moon from sphericity, and all the investigators have agreed that a large bulge exists, though the exact size was not accurately determined.

From the measures of the tiny but brilliant crater Mösting A, which is close to the center of the moon, Hayn (108) found the semiaxis which points to the earth to be 1.0023 long, where the unit is the average radius in the plane of the sky. Hayn candidly admitted that the accuracy of the result is low. Since 10^{-5} of the radius of the moon is 57.1 feet, the bulge so derived is about 13,000 feet high.

Pickering (6) found 1.0013 $\pm$ 0.0012, but his measures were made on 20 points, all within half a radius of the mean center of the disk, and because of the small leverage which these restricted points supply, the probable error is large.

Franz (5) made the most important effort. He measured these minute shifts for fifty-five small craters spread widely over the lunar disk and derived a value of 1.00114 $\pm$ 0.00039 for the x semiaxis. The bulge is thus 6,500 $\pm$ 2,200 feet high.

Saunder (6) measured 1.00052 $\pm$ 0.00027 from 38 points on four negatives. The chosen craters are essentially on the central meridian. This

answer means a bulge of 3,000 ± 1,550 feet However, if Saunder leaves out the values for Anaxagoras and Anaxagoras a, the two points farthest north he finds 1 00123 ± 0 00029—very similar to the results of Franz and Pickering

Saunder made a deliberate attempt to determine the eccentricity of the prime meridian only but, except for his selection of points according to their longitude, neither Saunder nor Franz has tried to analyze the raw data according to the nature of the region near each point For example, Saunder has included a few points which lie in the bottoms of deep craters In neither list are the points segregated because of their upland or maria locations

Both lists have been published in full, fortunately and consequently they may be so analyzed The results are quite amazing and prove to have several very important consequences

Before the measures of Saunder and Franz can be compared and combined, certain systematic differences must be eliminated The heights of the 55 points of Franz were measured with respect to a mean sphere whose radius was 1 00056 times that used by Saunder Hence 56 units must be subtracted from Franz s heights to put them on the same scale as that of Saunder In addition, the heights measured by both men correspond to the elevation of the rims of small craters above or below the mean sphere To reduce them to the true surface an average of 35 units or 2 000 feet, must be subtracted from all heights. Saunder reduced additional measures by Franz on 14 objects which were also in his own list A total of 205 units must be subtracted from these heights to bring them to the same scale as the others When these operations have been performed the heights are strictly comparable and we have 93 of them with which to deal Of these, 6 have been rejected because they are so situated that their positions relative to the undisturbed surface cannot be determined The remaining points are nearly equally distributed between maria and continental regions, 45 lying on the seas and 42 in the uplands Table 23 contains the 93 points at which the values in column 3 include all the systematic corrections just described The letters L or S tell the land or sea location of the point ρ is the fraction of the radius of the projected moon at which the measured point lies reckoned from zero at the center

Figure 24, *A* and *B*, shows the relationships derived by Franz and Saunder respectively, and the measured points from which they came

TABLE 23

Heights of Specific Points Relative to the Mean Lunar Sphere

Name	Location	Height above Mean Sphere (Unit = $10^{-4} r$)	ρ
	Franz		
Grimaldi A	L	−132	0 94
Damoiseau D	L	−201	87
Grimaldi f	S	−238	88
Pythagoras A	L	−203	98
Fourier C	L	− 44	83
Flamsteed d	S	−390	71
Gassendi a	L	−134	69
Sharp A	S	−200	86
Encke E	S	−235	65
Mare Humorum J	S	− 10	74
Weigel A	L	− 71	91
Landsberg A	S	−225	53
Landsberg d	S	−227	52
Landsberg	S	−131	44
Laplace A	S	−273	79
Lubiniezky C	S	+ 24	50
Gambart A	S	−123	33
Heinsius A	L	+ 38	67
Parry A	L	+ 33	32
Mare Imbrium D	S	−262	59
?	S	−193	37
Gambart B	S	−212	20
Lalande A	S	− 74	20
Thebit B	S	− 31	40
Mösting c	S	−210	15
Alphonsus A	L	− 30	24
Sinus Medii B	S	− 90	03
Airy Randkrater	L	− 48	31
Hipparchus F	L	+ 36	14
Hyginus	S	− 26	17
Manilius D	S	−104	26
Boscovich A	Omit	+102	25
Linné c	S	−129	58
Linné	S	−292	50
Silberschlag a	S	− 92	26
Dionysius A	I	+ 40	31
Menelaus	Omit	−121	38
Bessel c	S	−165	42
Sacrobosco A	I	+ 38	40
Buch γ	I	+ 32	72
Büsching C	I	− 32	64
Ross A	I	+ 29	42
Taquet A	S	−263	43
Bergspitze	I	− 35	83
Lacus Mortis B	S	− 77	74
Nicolai A	I	+ 4	74
Plinius A	S	−182	52
Jansen	S	+ 16	53
Baily A	S	− 73	83
Mare Tranquillitatis A	S	+ 81	64
Macrobius a	I	−182	75
Fabricius K	I	− 63	79
Anonymous	I	−113	90
Burckhardt C	I	−124	77
Taruntius A	S	− 90	0 77

TABLE 23—*Continued*

Name	Location	Height above Mean Sphere (Unit = $10^{-4}r$)	ρ
	Franz-Saunder		
Thebit A	S	− 68	0 37
Lalande D	S	− 98	16
Hipparchus G	L	+ 11	16
Triesnecker B	L	+ 25	13
Triesnecker	S	+ 17	10
Bode B	L	− 17	16
Archimedes A	L	− 61	47
Murchison A	S	− 24	07
Ptolemaeus A	Omit	−148	15
Herschel c	L	− 32	10
Mösting A	S	− 93	11
Rhaeticus A	S	− 59	10
Bode	L	+ 47	13
Bode A	L	− 17	0 16
	Saunder		
Near Lilius	I	− 92	0 79
Licetus H	I	−198	69
Orontius d	I	−145	64
Stöfler K	I	− 92	63
Orontius c	I	− 84	67
Purbach b	I	−155	46
Purbach A	Omit	−346	41
Lacaille D	Omit	−318	40
Arzachel A	Omit	−400	32
Alpetragius B	S	−150	28
Deluc d	I	−124	84
Deluc H	I	− 98	82
Hipparchus I	I	− 8	11
Hipparchus K	I	+ 25	12
Hipparchus F	I	− 70	09
Hipparchus H	S	−143	06
Archimedes c	S	−133	53
Archimedes b	S	−118	54
Kirch	S	− 77	64
Near Cassini	S	−156	67
Piazzi Smyth	S	− 79	67
Plato H	S	− 89	82
Anaxagoras a	I	− 11	95
Anaxagoras	I	− 3	0 96

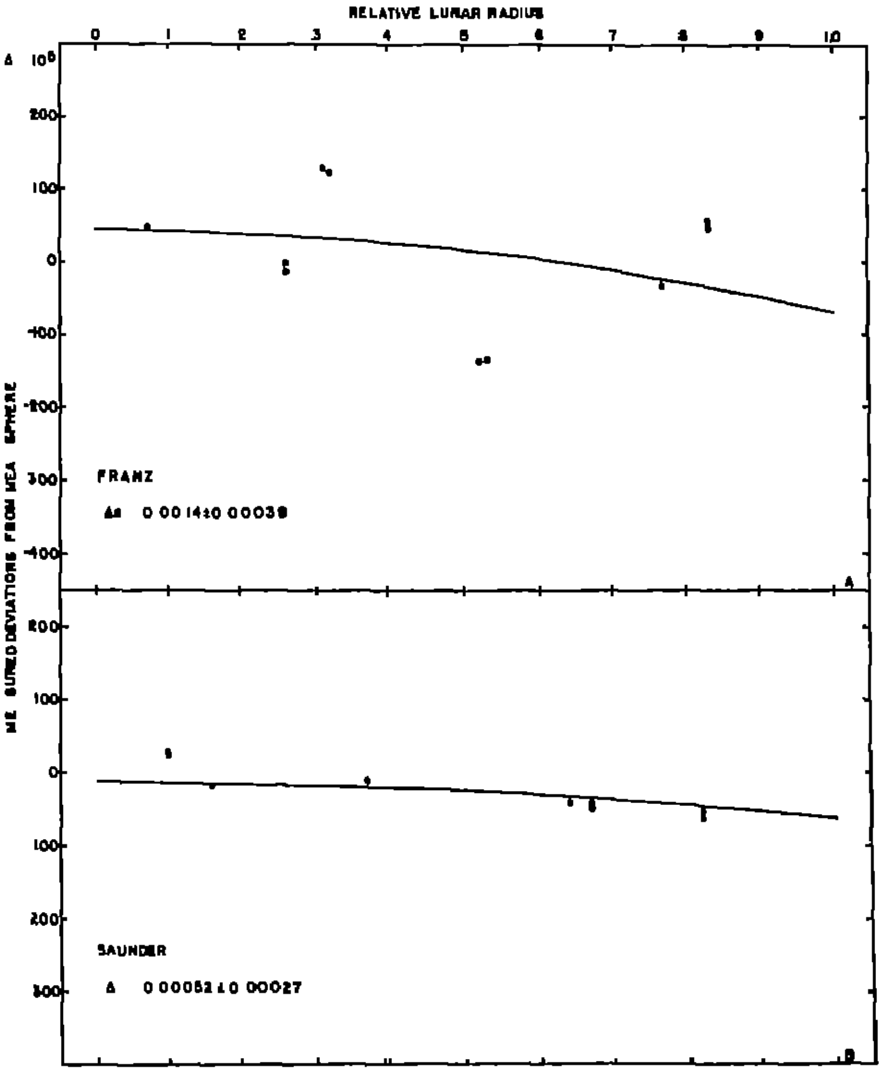


Fig. 24 — Tidal bulge of the moon according to Franz and Saunder. The lines show the measured curvatures but have been shifted vertically to a point midway between the land and sea positions.

The ellipticity correction for Saunder's measures is more apparent mathematically than to the eye, but the trend is clearly shown by Franz's data. In both cases the scatter is excessive

Figure 25, *A* and *B*, shows the relationships derived from the combination of the observations of these two men reduced to the same mean sphere, but separated into two groups, the first containing only those points lying in the bright upland regions and the second showing only the points lying on the maria. In both figures the same trend is apparent, much like that derived by Franz from his blended measures The scatter of the points around the mean curve is reduced by a factor of 2 for the

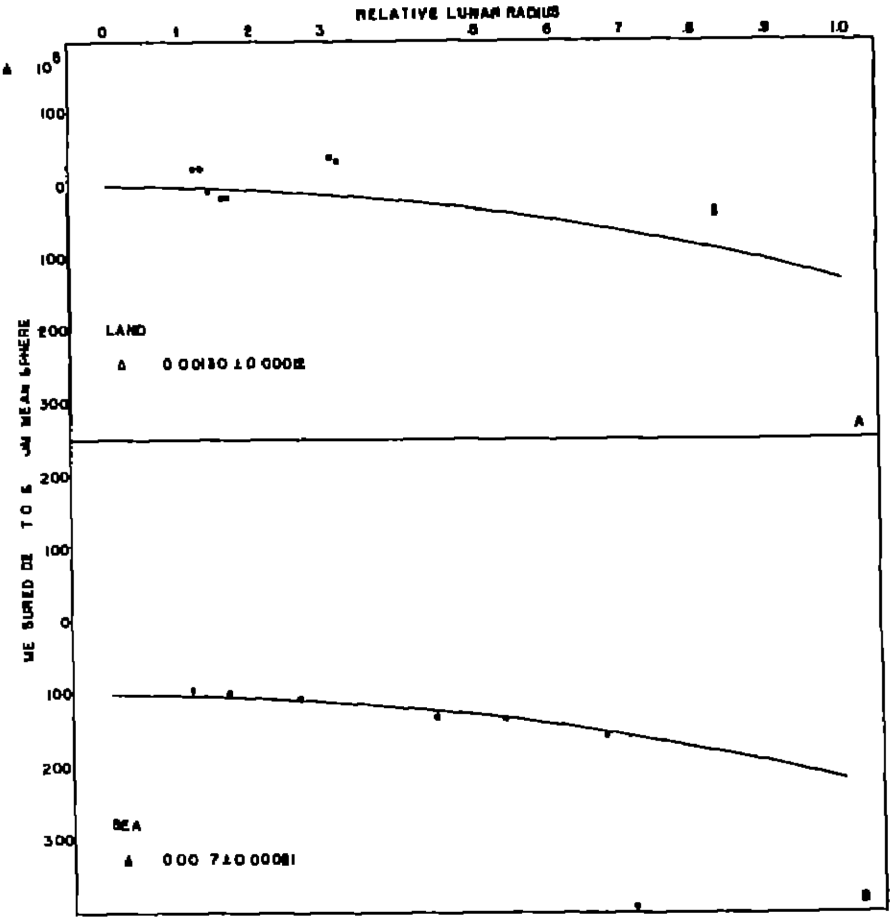


FIG. 25 —Tidal bulge of the moon in upland and maria regions

S points relative to Franz s result and by a factor of 3 for the L points In both cases the scatter is also much less than that found by Saunder Consequently, it is concluded that this segregation of the measured height differentials on the basis of the nature of the background surface is a valid and proper operation and that the difference between the two relation ships found in this manner represents a real and systematic depression of the maria relative to the upland areas The higher scatter of the points on the lava flows is due to real variations in surface level

The best fit to the L points (Fig 25, *A*) is given by

$$\Delta a = 0\ 00130 \pm 0\ 00012 \qquad (20)$$

Therefore the tidal bulge as measured on the bright areas is

$$7\ 400 \pm 700 \text{ feet} \qquad (21)$$

The best fit to the S points (Fig 25, *B*) is given by

$$\Delta a = 0\ 00117 \pm 0\ 00021 \qquad (22)$$

Therefore the tidal bulge as measured on the dark areas is

$$6\ 700 \pm 1\ 200 \text{ feet} \qquad (23)$$

However, the maria average 100 units, or 5,700 feet lower than the uplands near the center of the disk and 87 units or 5,000 feet, lower at the limbs The average depression of the maria is thus very close to 1 mile

As the height of the tidal bulge as measured on land and sea is the same within 700 feet or one part in ten, it is quite probable that the difference is not real and that all parts of the lunar surface are affected by the same tidal bulge regardless of local irregularities. The most probable value for the bulge then becomes

$$\Delta a = 0\ 00127 \pm 0\ 00010 \qquad (24)$$

In linear measure this means that the lunar tidal bulge is

$$7\ 200 \pm 600 \text{ feet} \qquad (25)$$

greater than the average radius in the plane of the sky

While the rotation of the moon was slowed originally by the friction of terrestrial tides formed in the lavas of the liquid body the lunar day is now held equal to the month by a tidal couple acting on the great central protuberance

The formulas of Appendix B may again be used to give the age of the moon when it solidified to the point at which it could no longer adjust in

form as the tidal pull of the earth relaxed Ages have been computed for the bulges found in equations (20) and (22) and for one probable error either way They are listed in Table 24 The values are lumped closely around an age of twenty five million years If the rate of recession of the moon proposed by Jeffreys had been accepted the measured tidal bulge would have been reached earlier in the moon s history

It seems unavoidable that the moon solidified very early in its life and has been of the present shape ever since If the recession from the earth had been at a linear rate which is certainly far slower than the truth the age at solidification would have been about six hundred million years or after slightly over one-quarter of geologic time had elapsed The length of

TABLE 24

AGE OF THE MOON AT SOLIDIFICATION

Location	$\Delta\epsilon$	Distance r/r_e	Time (Unit—10^6 Years)
L	0 00118	0 292	27
L	00130	283	24
L	00142	275	22
S	00096	313	14
S	00117	293	27
S	0 00138	0 277	22

time when the moon could alter its form to preserve an equipotential surface was certainly not over one-quarter and probably was considerably less than one twenty fifth of geologic time

According to Jeffreys (100) the earth s oceans were formed early in its life as soon as the average surface temperature dropped below the boiling point To judge by the rate at which the earth would cool this period must be considered to be negligibly small in proportion to the remainder of geologic time Indeed we may designate the condensation of the oceans as the beginning point of the geologic time sequence we can study In every geologic era we find evidences of sedimentary rock and hence of water action This holds true as far back as we can go in time For the earliest periods the Archeozoic and Proterozoic eras the extent of the oceans is not known In all later periods the continents were quite similar to those at present, the oceans lay mainly in their present beds but on numerous occasions thrust probing fingers—the vast shallow epeiric seas—feeling their ways over the land masses

We have three facts to use as a starting-point in our analysis. First, the earth is now slowing down in its rotation at the rate of one second per day per one hundred and twenty thousand years. Second, as the observed height of the lunar tidal bulge shows, the earth and moon were once at least as close together as 70,000 miles, or 0.3 of the present distance. Third, with the present observed amount of tidal friction, modified only by the changes of distance and tidal pull of the moon, a very great part of geologic time must have elapsed while the moon moved out to its present distance from 70,000 miles.

If tidal friction averaged less in the far distant past than at present, the recession of the moon would have progressed at a slower rate, and yet the date of the freezing of the moon's tidal bulge would have been only slightly later than has been suggested. This assumption implies that at some time in the more recent past the earth was slowed up at a faster rate than modern observations would allow. If the rate were faster in the first days of the moon, then the moon solidified even earlier in its history. Therefore, under any assumptions, the date at which the moon became rigid to the point where it ceased to adjust in shape to the reducing tidal pull of the earth was very far back in the past unless the tidal friction in the earth's oceans were missing or negligibly small before the critical point was reached. There is no evidence that such was the case and much evidence to show that the earth frequently sported shallow seas and straits where tidal friction would logically be expected to occur.

Consequently, there is every reason to believe that the tidal friction induced by the moon's pull on the oceans of the earth has existed throughout all geologic time much as we find it today except for changes in magnitude brought about by the variations in the moon's distance.

The dating of the origin of the fossil tidal bulge on the moon is thus upheld. The exact value determined for this event is unimportant. The important point is that this milestone in the moon's development occurred far back in the musty pages of Archeozoic history. If the moon were not born close to Roche's limit but out near a distance 0.3 times the present value, the foregoing arguments are strengthened.

It may be remarked in passing that the existence of a large fossil tidal bulge in the moon is strong evidence that the latter body came into being close to another large mass, i.e., the earth, and therefore the moon was always a satellite of the earth. This means that the moon was not formed as

an isolated body and then later was captured by the earth unless the capture occurred almost simultaneously with the birth

The maria are ancient lava flows. As such they must have obeyed the laws of liquids everywhere, and in flowing would always have followed downgrades except as forced by a head of liquid behind the front, pushing it on The lavas are distributed widely over the lunar surface and except in the broad portions of Oceanus Procellarum and Mare Nubium they are only a few thousand feet thick, for many crater rims extend above the lava crust These floods do not lie predominately near the limb but are found in to the very center of the disk

In short, the maria were formed by liquid lavas flowing over an equi potential surface marred only by local irregularities The very close agreement between the bulges measured on land and sea confirms this The tidal bulge, as far as the lavas were concerned, did not exist The maria were formed before the moon solidified to the point of rigidity They were formed so early in the lunar history that only a small fraction of the Archeozoic Era had passed All the Proterozoic, Paleozoic, Mesozoic and Cenozoic eras were yet to come

This observation hidden in the measures of the lunar figure by Franz and Saunder is most revealing It must completely revolutionize the theories of the history of the moon Its importance is still more evident when it is realized that if the maria are so old, then the great majority of the craters are even older for they underlie the maria Less than 10 per cent of the craters are postmare Consequently there was a very rapid accumulation of meteoritic matter early in the moon s career and a rapid tailing-off in frequency of impacts during the rest of geologic time

In the United States something less than 1 per cent of the exposed rock strata are of Archeozoic age (109) How many of these layers were laid down early in the era is impossible to say However it is in these few exposed strata that we should hunt for traces of the mighty impacts of the primitive meteorites which struck the earth at the same time the moon was being scarred for life Would such craters be recognized or recognizable after nearly 2 000,000 000 years of folding faulting metamorphism, and erosion?

Throughout the remaining 99 plus per cent of the continental United States—presumably a similar percentage obtains elsewhere—the meteoritic craters to be sought or now known correspond to the postmare strag

glers on the moon Even though the rate of fall decreased tremendously at first, the process has not stopped and some craters are even now being formed on the earth, and, of course, on the moon

It is the dark lava-covered areas of the moon which look the smoothest but the scatter of the points defining the bulge is nearly twice as great for the maria as for the brighter uplands. An examination of the measures in Table 23 shows that without exception the portions of the maria which lie farthest below the mean sphere are in Mare Nubium Oceanus Procellarum, and eastern Mare Imbrium, with a smaller separate group in Mare Serenitatis In the first and larger depressed area the western border runs north-south approximately through Eratosthenes The southern border is on a line running from a little south of Grimaldi to Sinus Medii

This border of the deepest section of the maria is almost exactly the one which divides the lava flow according to two other characteristics South of the line are numerous drowned craters whose rims peer up over the dense flood North of the line very few drowned craters may be seen

If the lava surface had been lower to the north originally, the flow would not have continued southward In all probability the lavas are deeper north of the line but there another factor must be called on to complete the picture The tremendous weight of the superimposed rocks caused an isostatic compensation to occur All sections of the maria sank, the deepest and heaviest portions sank farthest The parts of the seas which are most free of partially submerged craters are the deepest relative to the mean sphere Perhaps there really is an analogy between the lunar and terrestrial sea basins after all

This assumption of the presence of a primal isostatic compensation in the moon far in the past, does no violence to modern geophysical thought It is on the contrary, a well recognized and authenticated process, and it would be passing strange if the sheets of molten rock had not forced the moon s crust downward

E W Brown (110) whose peerless analyses of the motions of the moon are world famous, noted that the southern limb coming as it does in the bright uplands is actually farther from the moon s center of mass than is the northern limb It is in the north that most of the maria are found Consequently there is an independent observational proof that the principle of isostasy applies to the moon and indeed has operated there on a vast scale

The appearance of the premare craters lying along the shores illustrates the magnitude of the isostatic sinking of the lava flows The sides of the craters toward the sea are lower and some of the pits have been invaded by the floods

Because certain well-defined areas of lava sank more than did other regions, the present relative heights of two connected lava surfaces cannot be used to tell the original direction of flow

There is a still different set of observational facts which is nicely explained by isostatic compensation In Figure 13 the four different appearance (age) classifications of the lunar craters are compared by plotting log diameter against log depth Craters in Class 4 are more or less filled with lava and hence do not enter into this discussion but when the Class 2 craters are compared with the Class 1 craters it is found that the former are relatively shallower and that the difference in depth increases with increasing size of the crater The Class 1 craters are the newest—most of them are postmare in age—and presumably are younger than the time when the moon solidified to the point at which it could no longer adjust its form either isostatically or to the earth s varying tidal pull The Class 2 craters are the youngest premare pits

When a large crater is formed there is a sudden great relief of load on a circular section of the moon s crust A block many miles across and from 1 to 3 miles thick is lifted out and deposited in a circular ring around the hole If the loss of load were great enough and the lunar rocks weak enough the bottom of the crater would rise somewhat and the rise should be greatest for the largest craters.

The Class 3 pits are the oldest of all and the effects found at the Class 2 craters are present in exaggerated form Some of the Class 3 craters have been so deformed by rising floors that they have nearly lost the characteristic crater appearance The best example of this is Maginus The great Class 2 crater Clavius is another fine case The monstrous unnamed crater east of Walter while tentatively listed in Class 4 is certainly a structure whose depth has been greatly changed by an isostatic compensation

Scattered widely over the moon but predominately in the first three quadrants are hundreds of formations known as rills or clefts They are divided into two classes (111) The first contains those rills which are broad and shallow like long flat valleys Among these are the Hesiodus

cleft, Schröter's Valley, the Ariadaeus cleft, and the Hippalus clefts. Sometimes the two branches of the cleft of Hyginus are included.

The second type contains those objects which are narrow, deep, and steep-sided with serrated edges. Examples are the Triesnecker clefts and the Mersenius-Ramsden objects.

The rills of both classes are cracks in the lunar crust. Probably the only difference between the two is that the former have been more or less completely filled with lava. Usually it is only the largest of these open fissures which are in class 1.

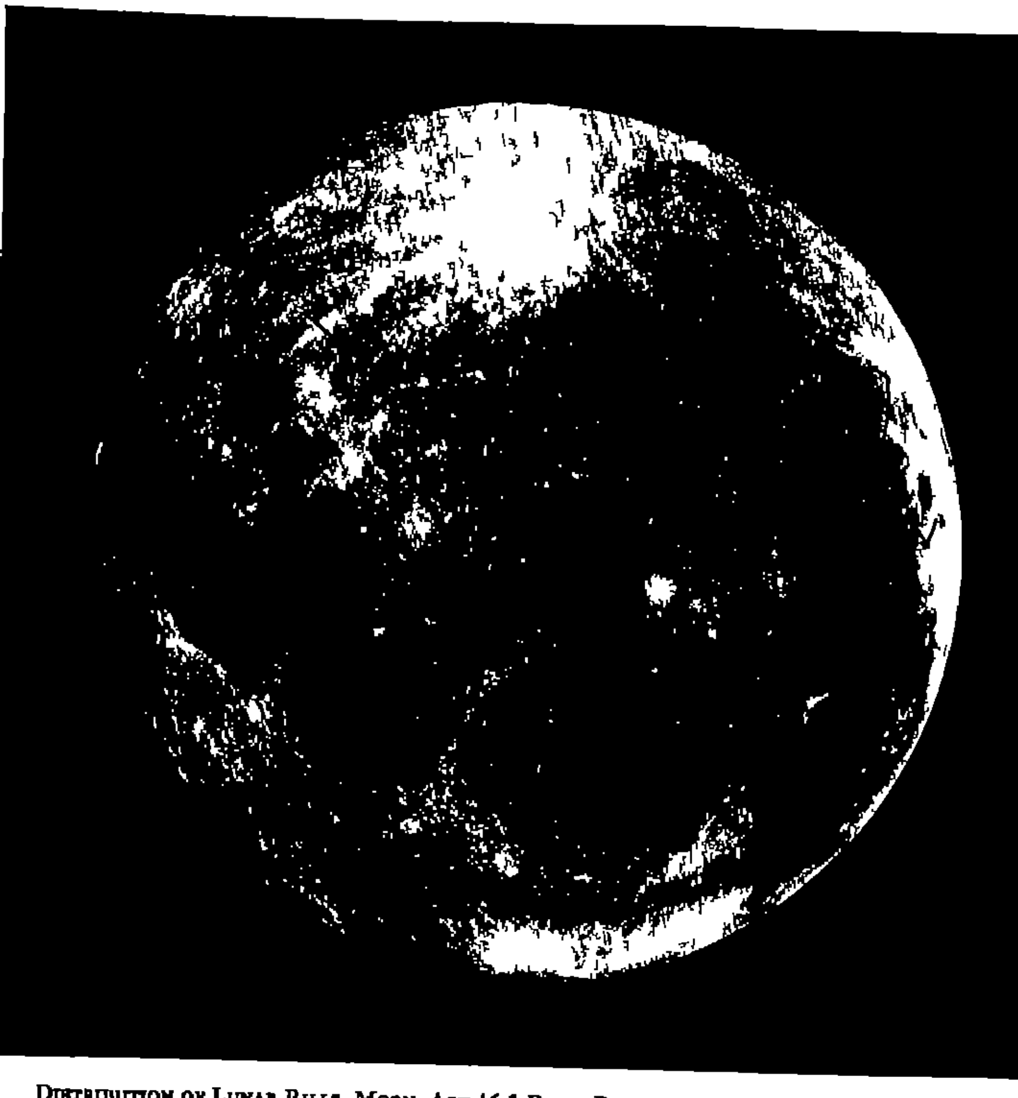
Pease, at the 100-inch telescope, noted that under moderate magnification the rills resemble deep, canal-like channels with roughly parallel sides, displaying occasional local irregularities and fining off to invisibility at one or both ends. But, if they are critically scrutinized under the best conditions and with high powers, the apparent evenness of the edges disappears and it is found that the latter exhibit indentations, projections, and little flexures like the banks of an ordinary stream or rivulet.

The openness of the rills marks them as places of tension in the surface where the weak points gave way. They normally run through surface features as though the latter were not present. The Hippalus clefts go for some hundreds of miles, splitting lava flows, mountainous masses, and crater walls alike. The Hyginus cleft divides the crater Hyginus into two nearly equal halves. The crater is not deformed; its parts have simply been thrust apart to the width of the cleft. In most cases, where it is possible to tell, the rills are among the youngest of the lunar structures.

If the nature of the rills is interesting, their locations are still more so. On Plate 15 are drawn the major rills and rill systems. It is immediately seen that they are not scattered at random, as are the craters, but show a definite systematic pattern. In the great majority of cases the rills mark the approximate edge of a lava flow. The plan is far too striking to be accidental. The edges of the maria were once regions of great horizontal tension. A second and less well-defined system of rills lies at right angles to the border clefts.

Mare Nubium, and its appendages, Mare Vaporum and Sinus Medii, are well outlined. Mare Tranquillitatis, for half its circumference, is defined by clefts. Mare Serenitatis is beautifully bounded, as is the southern, or Apennine front of Mare Imbrium. Mare Humorum is clearly set off from Mare Nubium by the Hippalus clefts, the Mersenius clefts, and

PLATE XV



Distribution of Lunar Rills Moon Age 16.3 Days, December 7 1938 (Lick Observatory)

others which follow the circular outline of the sea. The long Sirsalis rill is nearly parallel to the northeastern edge of Mare Humorum.

Because the rills are subsequent to the maria and yet are so clearly associated with their shores, some characteristic of the lava flows seems to have been the cause of the formation of these cracks. Probably the answer is to be found in the great forces involved in making the isostatic adjustments. Massive blocks of the crust sank, hinging on the margins between lava flow and upland. The rills developed in the pivotal areas.

Many of the larger craters, particularly the lava-filled pits, contain clefts in the interior. Pitatus, Gassendi, Petavius, and Arzachel are type cases. These crater rills seem, on a small scale, much like the Mare Serenitatis system of clefts.

Except for a few mountain ranges on the limbs which cannot be seen clearly enough to establish their nature, the great mountain ranges of the moon are all associated with the maria, forming borders of the circular seas. There is no single case of a mountain range like those known on earth.

Barrell (112) writes:

> Crustal wrinkling of the earth is not due to external cooling, as Dutton, Fisher, and Chamberlain have shown. Chamberlain has given cogent reasons for holding that this is due indirectly to a condensation of the nucleus of the earth and that the direct cause may be found in the enormous pressures acting thereon due to the weight of the lithosphere. This pressure attains 45,000,000 pounds per square inch at the earth's center, a depth of 3959 miles. The moon's center, at a depth of 1081 miles, is subjected to only a small portion of this pressure, equivalent to that which would be found in the earth somewhat less than 100 miles beneath its surface. This lack of high internal pressures seems, therefore, to explain the absence of important linear mountain systems on the moon.

The reduction in the lunar surface area as the primal tidal bulge subsided to its present dimensions was not large enough to produce a real mountain range of the compression-folding type known on earth. Surface shrinkage on cooling may even have compensated for the small compression due to change of form.

CHAPTER 11

The Circular Maria

THE normal sequence of crater changes with increasing size is well defined. Within rather close limits equation (7) will give the apparent crater depth for any crater diameter up to about 80 miles. How far beyond this point the equation holds is uncertain, for there are no larger Class 1 craters on the moon. The larger objects, Clavius, Maginus, Bailly, as well as many others, have been considerably modified since they were formed.

It is usually considered that approximately 150 miles in diameter marks the upper limit of crater size. A dozen objects are of that order of magnitude. There is a smooth decrease in numbers of craters of each diameter group as the diameter increases. It does not seem probable that this exponential decrease in frequency would suddenly cut off at this diameter. Instead, we would expect a few other larger craters to exist on the moon up to at least 300 miles in diameter.

When the face of the moon is searched carefully for these postulated giants, none is immediately apparent. True, there are several large, nearly circular formations, but in no case is there a duplication of all the crater characteristics. These structures are Mare Imbrium, Mare Serenitatis, Mare Humorum, Mare Nectaris, Mare Crisium, Mare Humboldtianum, Sinus Iridum, and the great bay enclosed by the Riphaen Mountains and covered by the lavas of Mare Nubium.

Two possibilities exist. Either these eight objects are extrapolated versions of the normal craters as we commonly recognize them, or else they represent entirely distinct types of lunar features. If the former interpretation is correct, we must be able to correlate various features of the circular maria with similar characteristics of the craters. Such a correlation means that the mode of origin of these seas is the same as that of the craters, and hence that all parts of their observed structures were caused by the impacts of vast meteorites, one per mare, and resultant reacting processes on the moon. If the second choice must be made, it throws serious doubt on the necessity of postulating a meteoritic origin for the

craters. The craters, without doubt, were born in great explosions. As far as is known, only the meteoritic-impact hypothesis furnishes the titanic amounts of energy needed. However, if it can be shown that processes inherent in the moon formed the mountain-bordered seas, then it is obvious that the moon possessed internal energies vast enough to account for all its surface markings.

In what ways are these eight objects like the craters, and in what ways do they differ? First, and foremost, both types of structure are circular, or nearly so. The maria are named thus because they have floors covered with lava. However, so do many of the craters, and thus the similarity is continued. In none of the eight great seas is there a central peak. In the larger craters the central peak is often found, but it is always relatively small; and, in each case, if the crater, such as Clavius, were filled with lava to the same extent as Mare Imbrium and others like it, the central peak would disappear. Therefore the absence of a central mountain peak does not argue against the essential similarity of the two sequences. The rims of the craters are mountainous. They are composed of jagged blocks of surface rocks blasted from the pit and deposited in a ring around the hole. The rims of these mountain-edged maria are also raised above the surface, are roughly circular, and are highest on the side next to the sea. The outer slopes are gradual, though extremely rough, and quite comparable in appearance to the outer walls of the larger craters.

It is when attention is directed to the inner walls of the mountain-walled seas that the first discrepancy is noted. Fauth (72) showed many years ago that the slope of the inner walls of craters was a function of the diameter of the crater. The larger craters had lower slopes. For the group of largest craters, averaging about 90 miles in diameter, the mean inner slope was nearly 12°. This value would undoubtedly have to be increased for the highest portions of the inner wall because the latter is usually concave, but even here the slope does not exceed 20°–30°.

On the contrary, the inner face of the mountainous border of each of the large circular maria is a fault scarp. Usually it is a nearly vertical drop of thousands of feet. Clearly there has been a tremendous subsidence of a nearly circular area in each case. The difference between the normal crater and the circular sea is contained in this observation. The craters are generally similar in appearance to the Mare Imbrium type structure, but fundamental differences exist.

If this were as far as we could go in the intercomparison, we should certainly have to conclude that the craters and circular seas were of different origin However a more careful analysis shows that this schism is not real and that the difficulty lies in the attempt to reproduce identically each feature of the craters in the seas and vice versa The magnitude of the effort necessary to produce a mountain bordered mare far transcends that necessary to yield a crater A simple extrapolation will not work nor should we expect it to One cannot predict the structure of a Theophilus from the characteristics of Piazzi Smyth, yet they are associated types

Nevertheless there exist markings on the moon which clearly identify the great, round seas as being the centers of explosions so mighty as to dwarf the crater forming blasts into insignificance

In Mare Vaporum is a series of formations which has been noticeably avoided by early selenographers They are valleys with raised borders, perhaps 10 miles wide and ranging up to 50 miles in length The best example points toward the north rim of Boscovich. Another lies between the latter and Hyginus. A third is in the hinterland of the Apennines while several are near Julius Caesar In practically every case the valleys have been invaded by the lavas of Mare Vaporum and thus being nearly filled are found primarily by the projecting rims. Those which are not lava filled are in the upland areas Northwest of Sosigenes is a groove which starts in the highlands and dips down beneath the Mare Tranquillitatis floods. It is filled by them, thus dating the series as having been formed before Mare Tranquillitatis and Mare Vaporum

Part of this group of elongated markings overlies the Haemus Mountains, the south border of Mare Serenitatis This arcuate range has been nearly destroyed One valley, starting not far from Aratus has completely wiped out the mountains as it plunges into Mare Serenitatis but the lava floor of the great sea has serenely flowed in over the valley and buried its western end The Haemus Mountains mark the birth of the main structure of Mare Serenitatis The valley system is subsequent to this yet no trace of the valleys are to be found on the smooth lava-covered surface of the sea The molten flood came considerably after Mare Serenitatis was born and has covered its floor thus obliterating any of these valleys lying thereon

These valleys do not have the characteristics of terrestrial graben or rift valleys In fact their like is only to be found when a projectile

ricochets from the ground without exploding or when a dud shell strikes the earth at a low angle and gouges out a long shallow groove.

That this explanation is the correct one may be guessed from the appearance of these and other similar grooves. Even more important is the surprising orientation of the valleys. Those objects in the Mare Vaporum region are almost, but not quite, parallel. They converge in a northeasterly direction; and, if each one is projected in the convergent direction along the arc of a great circle, the family of arcs intersects, not in a point, but in a circular area near the center of Mare Imbrium. This is the same area as that outlined by a ring of occasional mountains and small mountain ranges extending above the lava floor. This ring is well over 300 miles in diameter.

The Mare Vaporum system of radial valleys is relatively close to Mare Imbrium. East of it and about the same distance behind the Apennines is an upland area surrounding Ukert. Within a 20-mile radius from this crater are twelve of the radial valleys. In each case, the valleys appear on the highest portions of the irregular surface.

When this area is near the terminator, it can be seen that the entire raised zone dividing Mare Vaporum from Sinus Aestuum and extending to Schröter is stippled with similar markings, less well defined. Thousands of them point accusingly toward Mare Imbrium. The long, slightly raised region between Copernicus and Fra Mauro is of similar type.

The outlines of large parts of these two areas are softened and muted; the color tints are changed from normal as if they had once been covered briefly by the molten flood which quickly withdrew before solidification.

The radial valleys in Mare Vaporum are prelava. When the liquid came, it did not succeed in covering them. In other near-by lava flows the valleys are not found, yet immediately south and southwest of the Sinus Medii is the greatest development of the Imbrian system.

East of Ptolemaeus are many beautiful examples. They are sharp and clear cut, averaging perhaps from 2 to 3 miles broad and from 5 to 40 miles long. Immediately west of Herschel is a tremendous gouge which may be composite. Near Godin and Taylor are other long grooves. The entire rims of Hipparchus, Ptolemaeus, Albategnius, and Alphonsus are shattered by uncounted troughs which clearly have selected the highest places for their appearances.

In one of the very few references to these valleys in the literature,

PLATE XVI

SPLASH CRATERS RADIAL TO MARE IMBRIUM IN THE REGION OF THE HAEMUS MOUNTAINS AND MARE VAPORUM (YERKES OBSERVATORY)

Steavenson (21) suggested that they were due to tangential impacts of a swarm of meteorites, not realizing that they formed part of a larger system Only the most prominent have been pointed out Hundreds or thousands can be detected more easily either by the telescope or on good photographs

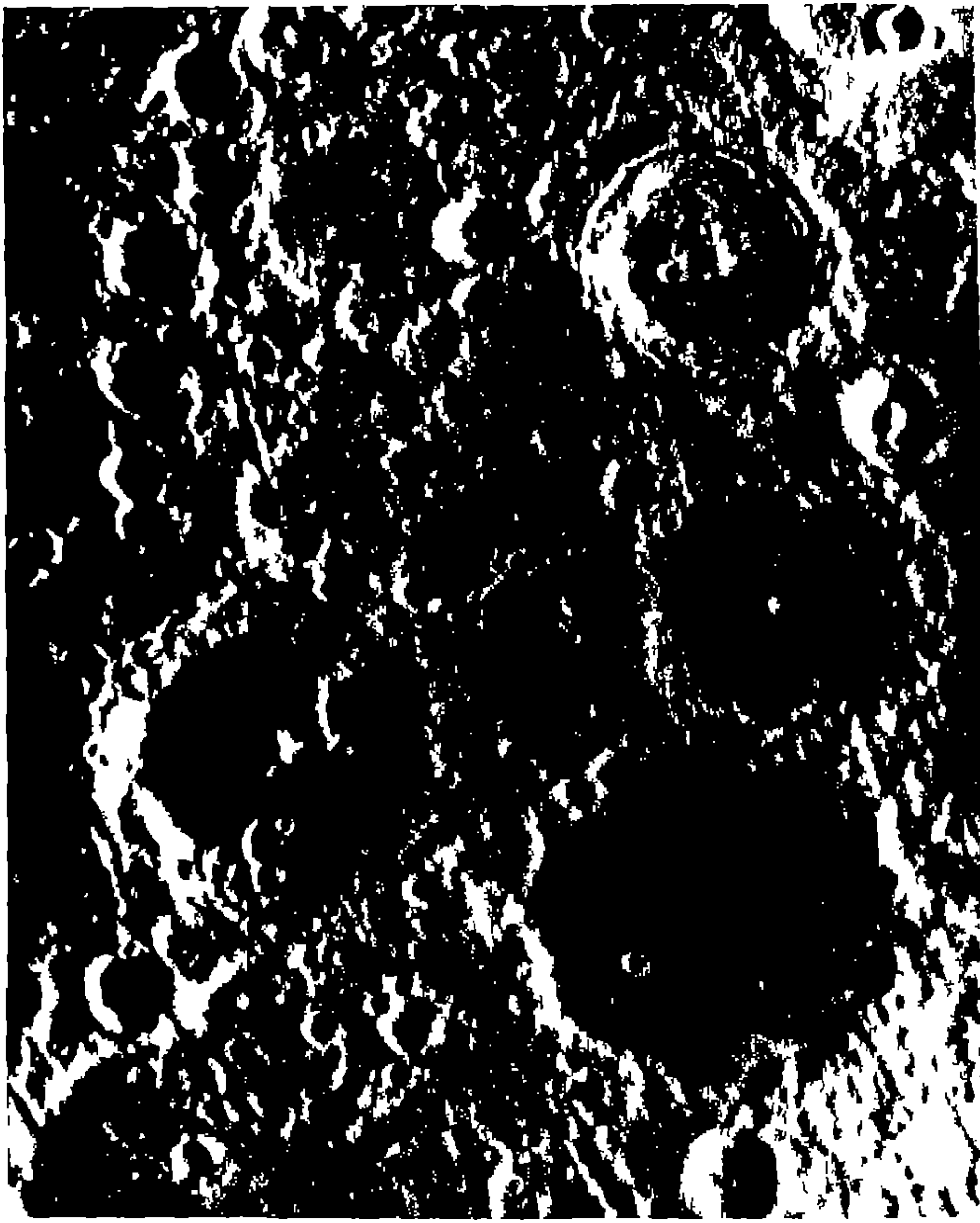
In any local area these grooves are nearly parallel but the change in their azimuths is clearly seen by comparing the Mare Vaporum and the Ptolemaic valleys Over the entire region the markings are like the ribs of a fan centering near the middle of Mare Imbrium

The lava flows again allow a relative dating of the sequence of events The radial markings developed after most of the craters, for the latter are seriously deformed A few craters such as the small one 15 miles west of Hind, are later structures The valleys are premare Therefore even the inland craters are earlier than the seas for the most part In Fra Mauro and Bonpland covered by the lavas of Mare Nubium, we may still see the outlines of nearly buried valleys radial to Mare Imbrium On the floors of Albategnius and Hipparchus are numerous such traces Consequently the lavas in the great craters now bordering the major lava flows were not generated by the craters themselves but have seeped in from the main flow The mechanism of this infiltration is not clear but in all probability the crater walls are honeycombed with cracks and faults which would allow the very fluid rocks to enter The entrance to Hipparchus is visible, coming from Sinus Medii The lava filled craters are usually found near a mare but a direct visible connection is not often apparent Nevertheless the lavas from the seas did enter and flood the crater bottoms

For 180° the area covered by Mare Nubium and Oceanus Procellarum prevents any of the valleys which might have been formed in these directions from appearing Beyond Mare Frigoris to the north foreshortening adds to the difficulties of their detection but even here enough of the radial markings have been found to insure that the great fan is opened throughout 360° Most of these valleys lie to the northwest Several start near Archytas

Closer to the great Imbrian sea cutting nearly through the Alps is the magnificent Alpine Valley nearly 6 miles wide at its broadest point and over 80 miles long It does not touch the lavas of either Mare Imbrium or Mare Frigoris starting in the wildest and most jagged section of the mountains and fining out just before leaving the uplands A depth of

PLATE XVII



Splash Craters Radial to Mare Imbrium in the Region of Ptolemaeus (Mt Wilson)

11,000 feet has been suggested (19) for the valley, but this is certainly an overestimate for most of the length and can refer only to the differential between valley and occasional near-by mountain. Its bottom appears to be flooded.

Under certain angles of illumination[1] the entire Alpine region and northern Caucasus may be seen to be furrowed by very shallow valleys, all part of the same great Imbrian fan of radial markings.

Mare Serenitatis completes the circle, hiding under a lava umbrella any valleys which were formed to the west. Throughout the entire 360° surrounding Mare Imbrium wherever the lavas flows connecting with Mare Imbrium have not overflowed the surface, the radial valleys are found. One other associated type of feature is present. East of Copernicus are the Carpathian Mountains sloping southward into Mare Nubium. These rocky masses have been carved into ridges which perhaps are the raised sides of valleys nearly hidden by the lava. The appearance of these mountains is quite different from that of the Haemus Mountains, and the ridges seem to be features of the mountain-forming processes, not subsequent effects. They also point to the same section of Mare Imbrium as does the true valley system.

All the variety of lunar surface features oriented toward the central area of Mare Imbrium lie beyond the escarpment and most of them beyond the mountains out to extreme distances of approximately 800 miles. One possible distant member has been found. A valley cuts across Capella just north of Mare Nectaris, and this dates the Mare Nectaris formation as probably older than Mare Imbrium, for Capella seems to be younger than Mare Nectaris.

A structure of the magnitude and type of the complete Mare Imbrium system is unknown on earth. If the center of this sea were placed at St. Louis, Chicago would be in the lava-covered area. The escarpment would nearly reach Milwaukee on the north, Wichita on the west, Cincinnati on the east, and Birmingham on the south. The Apennines would cover half of Iowa and reach to Minneapolis. The Carpathians would lie near Grand Rapids. The Alps and Caucasus ranges would cover most of Kansas and Oklahoma. The radial valleys would be found from Winnipeg to Brownsville. The Capella straggler would nearly cut across Glacier National Park in Montana.

1. Lick photograph of January 11, 1938; moon aged 10.35 days.

The existence of thousands of valleys all perfectly aligned with one small area of the moon's surface the way the valleys prefer the higher land masses and the appearance of the valleys themselves are conclusive evidence that they were formed incident to some tremendous happening near the center of Mare Imbrium This happening was an explosion so violent that we must associate with it the formation of the sea mountain border and radial markings The latter were formed by the nearly horizontal ejection of thousands of masses large and small Those bodies with velocities less than 1 mile per second fell back to the moon and gouged out the radial valleys which may well be called "splash craters" The higher velocity masses departed from the moon

This system of valleys is simply an exaggeration of the structure surrounding so many of the newer-appearing craters such as Aristillus and must have been produced in the same way

The theory that the splash craters were gouged out of the moon's face by low angle impacts of debris from the Imbrian explosion must stand or fall on the mechanical ability of such flying fragments to produce the grooves

Experiments over the past century (113) starting with Didion at Metz France in 1834–35 and culminating with the modern knowledge of the penetrating powers of shells and fragments into concrete demonstrate the sufficiency of the process (see Appen C) Large masses of rock hurled from the region of Mare Imbrium and moving nearly 1 mile per second would be able to penetrate several miles into 5 000 p s i concrete or perhaps somewhat less into solid granite or basalt However the moon's features which are usually crossed by the radial valleys are crater rims and other surfaces which are composed of fragmented and brecciated rock The resistance offered by such materials is many times less than solid rock although perhaps higher than would be developed by sand and gravel Experiments on a small scale indicate that a sphere of density 3 diameter 1 mile moving 1 mile per second could penetrate concrete to a depth of 4 miles would plunge 8 miles through a mixture of sand and gravel and considerably farther through various soils and clays The equations in Appendix C indicate a penetration of 75 miles into moist clay

The data presented thus show that although the extrapolation is long grooves of the order of size of those seen scattered over the lunar surface

could have been produced by the process suggested, particularly when it is considered that the striking body probably was not completely buried. A glancing blow always causes a shallow trough several times longer than the depth to which a similar body could penetrate upon a normal impact. A splash crater of this type should average considerably broader than the diameter of the projectile.

So far, then, there is no presumption against the theory that the radial furrows were produced by colliding bodies coming in to the surface at very low angles. The evidence is entirely in favor of the suggestion.

The association of all these features with Mare Imbrium implies that either a single action produced the entire system or the splash craters were formed later—they certainly were not pre-Imbrium. There is no evidence that an explosion of the requisite power occurred after the sea and its mountainous borders were built. Therefore it is concluded that the entire associated system of structures had a common origin in a magnificent explosion.

For short distances where the moon's curvature may be neglected,

$$R = v^2 \sin \frac{2\alpha}{g}, \tag{26}$$

where R is the range, v the velocity, α the angle of projection, and g the gravitational acceleration.

The average distance to which materials were thrown from a typical splash crater was about 6 miles. If $R = 6$ miles $= 32{,}000$ feet, $\alpha = 45°$, $g = 5.4$ feet per second^2, then $v = 410$ feet per second. This value may be considered the average velocity at which the materials were gouged out of the splash craters. A typical splash crater is 40 miles by 5 miles by $\frac{1}{2}$ mile. The volume displaced is nearly 4×10^{17} cc. If the density of the lunar crust, ρ, equals 3, the mass is approximately 10^{18} gm., and the kinetic energy of its motion during displacement is 8×10^{25} ergs. At least this amount of energy must have been applied locally to the lunar surface to produce a typical splash crater.

It would take a body at least 1 mile in diameter moving 1 mile per second, composed of lunar rock, to plow out such a furrow, for the kinetic energy of such a mass would be 8×10^{25} ergs. As a very rough guess it may be estimated that the energy released in the main Imbrian explosion was a

million times greater This kinetic energy would be given up by a spherical mass of nickel iron 10 miles in diameter striking with a velocity of nearly 20 miles per second These crude stabs may suffice to indicate the order of size of the meteoritic body which could cause an explosion of the necessary magnitude The suggested dimensions are not wildly different from those which might have been expected from the calculated sizes of the meteor ites which could produce the normal craters (Table 14) Some hundreds of asteroids are of this size or larger

There are other features of Mare Imbrium which are not explicable as immediate results of the explosion The first of these is the sharpness of the fault scarp bordering the lava The internal faces of the mountain ranges, and particularly the Apennines, show that a tremendous landslip has occurred Second surrounding probably the entire mountain ring is a concentric lava filled depression visible on the north and south for a total of about two-thirds of its length Any acceptable hypothesis must account for both features, for they are integral components of a unified assembly The same hypothesis must also locate the center of the explosion which initiated the sequence of events and account for the apparent lack of a yawning crater far larger than Clavius

Let us review the complete process Before the impact Mare Imbrium and all the appended lava flows did not exist Mare Serenitatis was present probably not lava filled but bordered by two proud and high ranges, the Haemus Mountains and the Caucasus The southern section of Serenitatis looked much as portions of the northern half do now spotted with craters many of them blurred and overlapping Where Mare Im brium was to come was a broad upland dotted with thousands of craters large and small Sinus Iridum had not yet raised its massive ramparts to catch the morning sun

Downward the meteorite plummeted from the northeast gradually gaining velocity Probably it did not even glow from the effects of the nearly absent lunar atmosphere Then it struck the surface and quickly disappeared beneath leaving a small sharp hole to mark its passage For only an instant however did the calm prevail for then all hell broke loose, soundlessly on a scale to shame the infernos dreamed of by little men A great section of the crust several hundreds of miles across domed up, split rapidly and radially from the central point Surface layers peeled back on themselves like the opening of a gigantic flower

followed quickly by a stamen of dust and fragments spreading rapidly in all directions without the roiling turbulence imparted by an atmosphere.

The unfolding of the initial dome had a shielding effect and thus created a null zone surrounding the great pit. Most of the matter lifted from the crater was deposited in this protected area, raising a broad and low rim of mountains. Higher-velocity fragments, spewed forth nearly horizontally, smashed great furrows into the moon's face during the succeeding 20 minutes, furrows radiating outward from the explosion focus. Some of these bodies were the ones which so nearly obliterated the Haemus Mountains.

The activity died down. Some matter had exceeded the velocity of escape and was henceforth lost to the moon. Other fragments struck, ricocheted, struck again, and came to rest. Dust and larger blocks rained down on all portions of the moon. Soon all was quiet. The chasm just born was about 350 miles across and perhaps 6 or 7 miles deep relative to the curving surface. Actually it probably was slightly convex rather than concave, for the moon is a rather small body.

Surrounding the crater the rim was quite unsymmetrical. In the north its width was about 100 miles. On the face which now forms the Apennines, opposite the direction of approach of the meteorite, it was over twice as wide and correspondingly more jagged. The extreme roughness of the mountainous border makes it evident that its materials were emplaced violently.

The first of the two major changes in the moon was the crater and its rim. The second was far more subtle. When the meteorite struck, not only did it release bountiful supplies of energy, it transmitted a tremendous quantity of momentum. The crust of the moon absorbed this shock; it had to, but when the pressure was released, a tremendous rebound followed. A great segment moved upward, forming a mound, which, being completely damped by tension fractures, became fixed as a structural dome. The crater was perched slightly north of center.

This massive dome, 800 miles across, was completely surrounded by a ring syncline. Still farther away a weak ring anticline was raised, forming the outer edge of the syncline. This is the exact pattern always found when elastic substances are suddenly disturbed.

An appreciable interval of time passed before the next stage in the drama unfolded. A large meteorite fell, and the crater Archimedes arose

to mark its passing A still larger body formed that near-duplicate of Clavius whose remains we now know as Sinus Iridum Both structures developed on the dome

And then the great central block of the dome nearly circular, began to settle Long held higher than hydrostatic pressure would permit by the strength of its own rocks acting as keystones the mass slipped downward Ring faults probably formed during the raising of the mound acted as slides The Apennine section dropped a good 10,000–12 000 feet perhaps more The opposite face slid nearly as far Sinus Iridum split in two one-half remaining on the raised rim of the new and larger Mare Imbrium pit the other dropping deep into the abyss

As the great millstone sank huge columns of superheated magma welled and bubbled up probably coming mainly from the ring faults As at a great reservoir the liquid filled the vast depression, buried the moon's greatest crater until only an indicated ring of isolated mountain peaks remained to mark its rim then burst its bonds to the east and spread rapidly out to produce Mare Nubium and Oceanus Procellarum North and south the liquid sped around the mountains into the ring syncline where it buried many craters and splash craters On the west the gap between the Caucasus and Apennine ranges offered easy ingress to Mare Serenitatis whose southern floor was soon covered Beyond the Haemus Mountains the lavas raced, filling Mare Tranquillitatis Mare Foecunditatis and even stretching a ribbon into the basin centered in the Altai Mountains thus bringing Mare Nectaris into being (see p 214 concerning the velocity of the lava flow)

To the far west little isostatic compensation occurred the sheets were relatively thin Mare Serenitatis was an ancient structure of the Imbrian type Its floor sank somewhat under the new load as the height measures of Franz have shown The once level liquid surface now shows a decided slope down from Mare Tranquillitatis into Mare Serenitatis

To the east the main mass of the magma poured East of Mare Imbrium the crust sank considerably It is even possible that the load caused so great an adjustment to occur relatively quickly that the eastern mountain border disappeared beneath the surface except for the scattered Harbinger peaks The steady eastward dip of the Carpathians and the mountains on the northeast of Mare Imbrium support this view However in all cases

the main isostatic adjustment was a gradual process which developed its main action after the lavas had frozen.

A block of 400,000 square miles, the area of Mare Imbrium, sinking 2 miles, must displace 800,000 cubic miles of magma.

Lava flows cover about one-third of the visible surface of the moon to a depth averaging about one-half mile, judging from the protruding crater rims. A total volume of lava of approximately 1,000,000 cubic miles is indicated. The agreement is probably better than we have any right to expect.

At least three separate sheets of lava spread from Mare Imbrium. The first was dark and highly mobile; it flowed the greatest distance. Somewhat later a lighter-colored lava rose and painted a thin coat over western Mare Imbrium and all save the border of the primal flow in Mare Serenitatis. From the region of Sinus Iridum another dark flow outlined the northeastern quadrant of Mare Imbrium. The lost half of Sinus Iridum can be traced by low ridges on this lava.

It is necessary to know whether or not the lava could remain liquid long enough to cover the wide expanses now called maria. If not, then other sources of lava than the Imbrian must be found.

It must be postulated that the lava was extremely fluid because of the distance it spread and because of the confined places into which it penetrated. Consequently it probably was a basic lava and very hot. Highly acid lavas are more viscous. Basic lavas are usually about 10 per cent denser than acid lavas. Thus the isostatic changes would be augmented, particularly if the bright areas of the moon are acidic in nature.

On the airless moon there are only three methods of heat loss: radiation to space, conduction to the ground, and the carrying-away of energy by escaping gases.

Let us assume that the lava was at 3,500° K. and the ground at 100° K., a difference of 3,400° K. The initial value selected is not critical except that the temperature must be well above the freezing-point of the lava. The heat conductivity of basalt, granite, and other igneous rocks is about 0.005 calories per second per square centimeter, and so the heat loss by conductivity would be 17 calories per second per square centimeter. This value is a very high maximum, for as the temperature gradient between ground and lava decreased, the rate of heat flow would decrease.

The moving lava could not form a crust until the main mass was nearly ready to solidify Portions of the upper surface might harden but the rock would fracture and then the blocks would be rolled into the still hot magma where they would be remelted, thus forming a somewhat cooler layer on top

Let us assume that the radiating surface was 3 000° K hot According to the Stefan Boltzmann Law

$$E = \sigma T^4 \tag{27}$$

a black body at 3 000° K radiates 111 calories per second per square centimeter This, too may be considered a maximum rate As a fair guess it may be estimated that not over 10 calories per second per square centimeter could be carried away by escaping gas

We may neglect the transfer of heat sidewise in lava sheets as large as these are Therefore a maximum rate of heat loss is about 140 calories per second for each column of lava 1 square cm in cross-section Each column will average about one-half mile high

In order to cool 1 cc of rock from 3 500° K to 1 200° K near the point where the viscosity increases rapidly over 700 calories must be lost The specific heat of basalt averages about 0 25 In each column at least $4\ 5 \times 10^7$ calories must be lost before the lava sheet will stop rolling At the rate of 140 calories per second this would take nearly four days At 15 miles per hour the lava front would cover 1 200 miles This seems like a reasonable speed, and yet it certainly is higher than the actual rate of flow By the time the upper layers had cooled to 2,000° K the total heat loss per second would be 50 calories per square centimeter while the available supply of heat would not have decreased in proportion Therefore the maximum rate of flow needed to carry the lavas to the greatest distances observed may have been less than 10 miles per hour All connected lava sheets then could have arisen from a central source in Mare Imbrium It is clear that this molten rock developed from the still hot body of the moon and was not generated by the meteoritic explosion for the violence and rapidity of the latter were too great

In chapter 2 it was shown that Mare Imbrium was the most perfectly developed of all the large mountain bordered seas as well as the greatest Its features are reproduced with only local variations at other similar structures, although the characteristics which set these maria off as dis-

tinct from the normal craters grow less and less well defined with decreasing mare size until the smaller seas and the largest craters are quite similar There is no break in type with increasing size It is merely that the forces involved became so stupendous that additional structural modifications became necessary at the larger objects

Among the local variations the sizes of the valleys radiating from Mare Nectaris are outstanding, but the relative dimensions, length and width, are similar to those of the Imbrian valleys. The depths of the former are comparable to and hence relatively shallower than, those of the latter As the penetrating power of a projectile at a given speed is proportional to its diameter, the excessive size of these furrows is not alarming One of the Nectaris valleys goes westward for 500 miles moving across Snellius, but is visible only in disconnected sections The great projectile which produced it touched only the high spots and thus again evidenced the peculiar mode of origin of these lunar furrows

Mare Serenitatis and the Mare Nectaris–Altai Mountain system are the oldest of these strange supercraters Mare Imbrium is the youngest except for Sinus Iridum, which is essentially a contemporary formation

At each of the eight objects of this type the mountainous border and inner escarpment are present The outer ring syncline and suggested ring anticline may be found at Mare Imbrium, Mare Humorum Mare Humboldtianum and Mare Crisium The lavas of Mare Nubium would prevent its appearance at the Riphaen Mountains

The radial grooves and valleys are prominent at all save Mare Serenitatis and the Riphaen structure They are most numerous and distinct at the two largest systems and grow less well defined with decreasing mare size The Sinus Iridum radial furrows are only slightly exaggerated versions of those found at Aristillus Because of their mountainous locations they do not seem as prominent as at many of the larger craters, but they are easily visible to anything more than a casual glance

The elevator floor is beautifully shown at Mare Imbrium It sank so far that only a small section of the prelava surface is visible above the mare near Archimedes At Mare Nectaris the subsidence within the Altai ring sufficed only to bring the dome down to the normal level No magma was displaced in this collapse The large crater Fracastorius came into being after the Nectarian basin was formed The fact that it is nearly buried in the lava flow indicates that the flood came later and may thus be identi

fied as a part of the Imbrian outpouring to which it is connected At Mare Crisium and Mare Humboldtianum the lavas did rise and cover the dropping floor In the five largest examples there is clear evidence of a settling, or isostatic adjustment after the lava flows had hardened None of the large lava sheets is now level, even after the effects of the fossil tidal bulge are removed

The age-old history of the moon is thus a record of its birth near the earth and its liquefaction and solidification amid an explosive rain of meteoritic fragments Its face became scarred by at least a million craters visible from the earth and probably by billions of tiny pits The frequency of the impacts declined rapidly until at present such collisions are few and far between

The existence of small but authenticated meteoritic craters on the earth allows a tie-in to be made between the craters on the moon and the smaller man made explosion pits on the earth The identification of the source of the lunar craters as meteoritic impacts automatically follows from these correlations and from their visible natures. The meteoritic impacts only are known to be capable of furnishing the requisite amounts of energy Any nonmeteoritic hypothesis represents a fanciful extrapolation beyond anything known on earth

Every type of structure on the moon except two the low mounds and the chain craters can be easily explained as direct or indirect results of these collisions and explosions The domes and chain craters may well be mild igneous forms induced by the forces released at some of the larger explosions or they may be from forces inherent in the nature of the moon It does not matter There is no reason the dominant process should exclude other less important mechanisms from acting

Not only does the meteoritic theory explain the observed physical details of the lunar surface structure it allows for a satisfactory dating of the time of origin of these various features on a time scale which has no observed inconsistencies The random distribution of the craters also strongly suggests a nonlunar origin for the forces which produced the pits

The meteoritic impact theory of the origin of lunar structures is certainly sufficient to explain the observed characteristics It probably is necessary also The choice lies between a demonstrated process and one which has no basis in earthly experience

CHAPTER 12

Other Planets

THE earth and moon are not alone in space. They circle around the sun in company with eight other planets and a sky full of comets, asteroids, and meteorites. There is no reason to believe that the earth and moon were singled out for meteoritic bombardment in preference to the other bodies. Mars lies even closer to the belt of asteroids than does the earth, and hence its chances for asteroidal collisions would presumably be higher. Mercury lies closest to the sun with its great gravitational pull. It, too, should suffer numerous hits. The zodiacal light indicates that there is much finely divided matter near the sun and Mercury. All the terrestrial planets, at least, should be struck by extraneous masses at a rate similar to that of the moon and earth.

Venus and the major planets are cloud covered and we cannot see their surfaces. Pluto is too far away to examine. Only Mercury and Mars offer any possibility of exhibiting the effects of meteoritic bombardment.

No planet can be seen as well through any telescope as the moon can be seen by the naked eye. Hence definitive answers cannot be obtained. Nevertheless, Mars has been extensively studied, and certain facts are known. The planet has a rarefied atmosphere, but it would be a fairly good protection against tiny meteorites. Larger bodies would crash to the surface somewhat more easily than they do on earth.

Mars has no high mountains, and therefore it probably is not plagued with festering volcanoes. Certain areas on the planet, known also as maria, are depressed a few thousand feet below the general level. These areas thus bear a slight resemblance to either the lunar maria or the terrestrial ocean beds. They are not water filled but do seem to vary in color with the Martian seasons as though they were covered with vegetation.

Distributed widely over both the ocher deserts and the green maria are round dark spots, the oases, which conceivably could mark large craters

whose sunken floors would trap water vapor and hence permit a local vegetative covering

Certainly nothing conclusive can be learned from Mars now A few features suggest a possible similarity to lunar formations, but there the quest ends The distance to the red planet is too great when coupled with the turbulence of the terrestrial atmosphere

With Mercury the case is slightly different It is so close to the sun that it must be observed through disturbed air Daytime observation gives the best results Mercury has no air unlike Mars and hence polarization measures (11) may be made on light reflected directly from its surface rocks They indicate a condition almost exactly like that of the moon—a rough jagged rocky surface The reflection of light at different phases as well as the way Mercury reflects light of different colors emphasizes the similarity to the moon The surface of the moon was not rough until the meteorites made it so

On Mercury the temperature range (114) is from close to absolute zero on the dark side to a subsolar temperature of 683° K (770° F) hot enough to melt lead and tin

Antoniadi and Schiaparelli (13) have each drawn faint hazy dark markings on the tiny planet Although their maps are quite dissimilar in detail they are alike in the major features Through the telescope Mercury appears very much like a blurred version of the moon seen with the naked eye The dark Mercurian areas look much like lunar maria On both Mercury and the moon the dark markings are most prominent at the full phase Within the limits of observation Mercury seems to be a slightly enlarged version of the moon

The evidence sketchy as it is in most cases allows the interpretation that the terrestrial planets have been repeatedly struck by myriads of meteorites

APPENDIX A

Derivation of the Relationship between the Distance of the Moon and Geologic Time

Let

P_E = Angular momentum of earth's rotation,
P_M = Angular momentum of moon's revolution,
m = Mass of moon,
v = Linear velocity of moon in its orbit,
r = Distance of moon in terms of its present distance,
c = Circumference of moon's orbit (circular),
S = Period of moon's revolution (seconds),
T = Time in billions of years,
A, B, C, D, E = Constants.

$$P_M = m r v \ .$$

Assume that

$$\frac{dP_E}{dt} = \frac{A}{r^6} = -\frac{dP_M}{dt} ;$$

now

$$v = \frac{c}{S} = \frac{2\pi r}{S} ;$$

but

$$S = B r^{3/2} ;$$

therefore

$$v = \frac{2\pi r}{B r^{3/2}} = \frac{2\pi r^{-1/2}}{B} ;$$

therefore

$$P_M = \frac{2 m\pi r^{1/2}}{B} = C r^{1/2} ,$$

$$\frac{dP_M}{dt} = \tfrac{1}{2} C r^{-1/2} \frac{dr}{dt} ,$$

and

$$\frac{A}{r^6} = -\tfrac{1}{2} C r^{-1/2} \frac{dr}{dt} ,$$

$$\frac{dr}{dt} = D r^{-11/2} ,$$

$$r^{11/2} dr = D dt ;$$

therefore

$$\frac{2\,r^{13/2}}{13} = DT + E$$

When T was equal to 0 the month was 4 8 hours long and r was equal to 9 000 miles or 0 0377 Therefore

$$E = 0\ 000003$$

which is negligibly small When $r = 1$ $T = 2$, therefore

$$D = \frac{1}{13}$$

and

$$2\,r^{13/2} = T$$

When the assumed rate of loss of angular momentum of the earth s rotation is inversely proportional to r^3, the resulting equation becomes

$$2\,r^{7/2} = T$$

APPENDIX B

The Lunar Tidal Bulge as a Function of the Moon's Distance

The three axes, x, y, and z, of a homogeneous moon distorted by a tidal pull and centrifugal force of rotation are (100)

$$a\left(1+\frac{35}{12}\frac{M}{m}\frac{a^3}{r^3}\right), \qquad a\left(1-\frac{10}{12}\frac{M}{m}\frac{a^3}{r^3}\right), \qquad a\left(1-\frac{25}{12}\frac{M}{m}\frac{a^3}{r^3}\right),$$

where

a = The radius of the mean equivalent lunar sphere,
M = The mass of the earth,
m = The mass of the moon,
r = The distance of the moon in lunar radii.

The average of the y- and z-axes is

$$a\left(1-\frac{17.5}{12}\frac{M}{m}\frac{a^3}{r^3}\right).$$

Therefore the measured excess of the radial, x-, axis would be

$$a\left(1+\frac{52.5}{12}\frac{M}{m}\frac{a^3}{r^3}\right)=a\left(1+\Delta a\right).$$

To allow for nonhomogeneity, multiply the coefficient by 0.9; and to allow for elastic tides, multiply again by $1-k$, or 0.987. Therefore

$$\Delta a = 0.00002943\left(\frac{r_0}{r_1}\right)^3,$$

where

r_0 = The present distance of the moon,
r_1 = The distance of the moon when the tidal bulge equaled Δa.

APPENDIX C

The Penetrating Power of Projectiles

The equation of motion (113) of a body of mass m moving with velocity, v through a medium offering a resistance, R at any instant, t is

$$m\frac{dv}{dt}+R=0 \tag{A 1}$$

R depends on the cross-section of the projectile and the energy conveyed to the particles which are displaced at every instant and which is proportional to v^2 We may then express R as $Kr^2(\alpha+\beta v^2)$, where r is the radius of the body K is a constant and α and β are quantities depending on the medium

Equation (A 1) becomes

$$\frac{dv}{ds}\frac{ds}{dt}+\frac{Kr^2}{m}(\alpha+\beta v^2)=0 \tag{A 2}$$

which becomes

$$v\frac{dv}{ds}+\frac{3Kgr^2}{4\pi\rho r^3}(\alpha+\beta v^2)=0 \tag{A 3}$$

where ρ is the density of the body Therefore

$$\frac{v\,dv}{\alpha+\beta v^2}+\frac{3Kg\,ds}{4\pi\rho r}=0 \tag{A 4}$$

Suppose that the striking velocity is V After time t and distance, s the velocity has reduced to v Then

$$\int^{V}\frac{v\,dv}{\alpha+\beta v^2}=-\frac{3Kg}{4\pi\rho r}\int^{s}ds \quad \text{or} \quad \frac{1}{2\beta}\log\left(\frac{\alpha+\beta V^2}{\alpha+\beta v^2}\right)=\frac{3Kgs}{4\pi\rho r} \tag{A 5}$$

and from this

$$s=\frac{2\pi\rho r}{3Kg\beta}\log\left(\frac{\alpha+\beta V^2}{\alpha+\beta v^2}\right) \tag{A 6}$$

Changing to ordinary logarithms and substituting C for the constants π g K and $\frac{2}{3}$ we have

$$s=\frac{Cr\rho}{\beta}\log\left(\frac{\alpha+\beta V^2}{\alpha+\beta v^2}\right) \tag{A 7}$$

When $v = 0$,

$$s = \frac{C r \rho}{\beta} \log \left(1 + \frac{\beta}{\alpha} V^2\right). \tag{A-8}$$

Didion carried on a series of experiments at Metz, France, in 1834–35 with spherical artillery shot and derived the following values for the constants. In using projectiles of different sizes, C remains constant and equal to 156.5 if V is taken in meters per second, r in meters, and s in meters.

The corresponding constants for concrete (5,000 p.s.i.) have been derived from modern artillery experiments against typical shielding materials.

Substances	α	β
Sand mixed with gravel	435×10^3	88
Earth mixed with sand and gravel	600×10^3	120
Clayey soil	$1,045\times10^3$	36.8
Damp clay	266×10^3	21.7
Moistened clay	92×10^3	7.35
Concrete	43.4×10^6	40.5

These "constants" probably are variables which change as functions of the velocity and hence should not be used for velocities above the shock-wave velocity.

APPENDIX D

The Diameters of the Meteorites Which Produced the Craters

There exists a smooth correlation between the energy released by explosions close below the surface of the ground and the diameter of the resulting crater In Figure 26 the ordinate represents the explosive energy expressed in terms of the logarithm of the number of calories expended The abscissa gives the logarithm of the diameter of each crater expressed in feet All craters lie in soil The largest crater on which data of this type are known is the Hill 60 mine crater of World War I This is 340 feet in diameter, a fair approximation to a football stadium The smallest craters are from tiny mortar and artillery shells The relationship between diameter and depth of craters formed by explosions at the ground level is very similar to that found for subsurface bursts but far more energy is required to yield comparable crater dimensions According to recent navy experiments bomb craters in hard, striated rock are not significantly smaller than if they had been formed in soil Craters blasted from loose rock talus are nearly equal to those arising in soil

A very small but definite bending of the curve best representing the observed points is noticed Hence the extrapolation to larger craters is rendered somewhat uncertain The source of this curvature probably is to be found in the need for an increase in average fragment velocity with increase in crater dimensions However the energy necessary to produce the Arizona meteorite crater appears to be about 7.9×10^{13} calories or 3.3×10^{21} ergs Wylie s data in Table 9 chapter 7, correspond to 2.2×10^{14} calories or 9.4×10^{21} ergs The difference is a factor of 2.8 in energy or 1.4 in meteoritic radius The indicated solution would thus reduce the radii deduced by Wylie by a factor of 1.4 Wylie s value for the energy does not lie outside the limits of accuracy of the present solution (plus three probable errors)

A still greater extrapolation gives possible figures for the energy necessary to produce craters 1 20 40, 60 and 80 miles in diameter The

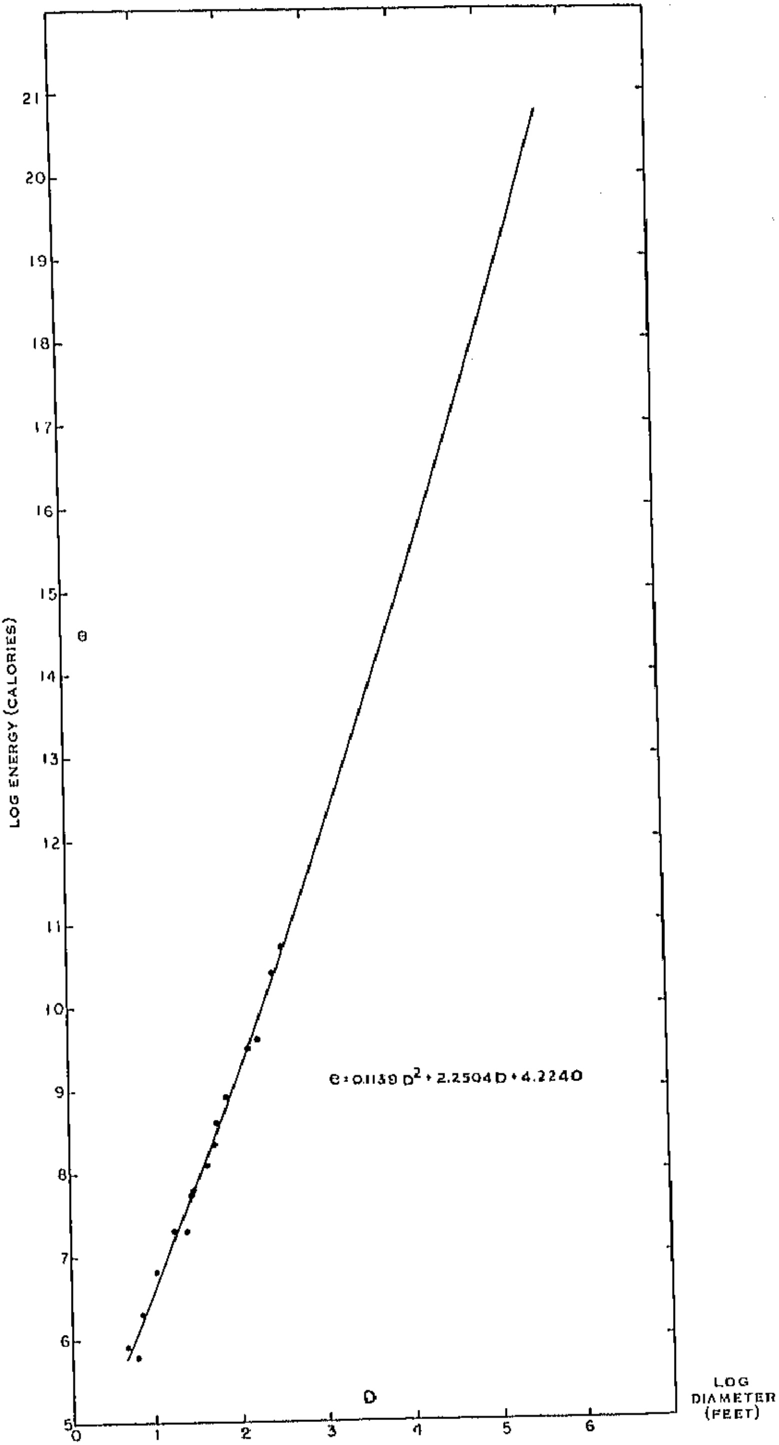


Fig. 26.—Relationship between energy expended and diameter of resultant crater (sub-

energies needed are, respectively, 7.4×10^{21} ergs, 1.0×10^{26} ergs, 1.1×10^{27} ergs, 4.4×10^{27} ergs, and 1.5×10^{28} ergs. If an impact velocity of 10 miles per second is assumed, these energies would be carried by spheres of nickel iron 39, 900, 2,100, 3,200, and 4,800 feet in diameter, respectively. These results have been listed in Table 14, chapter 8, where they compare favorably with the diameters derived from an assumed constant ratio between volume of material displaced and meteoritic volume. The correct order of size seems to be assured by the agreement between these two methods of attack.

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